Software Models for Relays

P. G. McLaren, K. Mustaphi, G. Benmouyal, S. Chano, A. Girgis, C. Henville, M. Kezunovic, L. Kojovic, R. Marttila, M. Meisinger, G. Michel, M. S. Sachdev, V. Skendzic, T. S. Sidhu, and D. Tziouvaras

***Abstract*—This paper reviews the past and present uses of relay models. It discusses the various types of models, what information is required to build such models and the model validation process. Examples of present and possible future use of software models are given.**

***Index Terms*—Relay models, relays, simulation, validation.**

I. Introduction

"SOFTWARE models," in the form of equations representing the operating characteristics of relays, have long been used by academics, manufacturers, and consultants for designing relays and checking their performance. These models describe characteristics which are defined in a variety of ways such as current versus time, differential current versus restrain current, and reactance versus resistance. The most familiar is the time-current characteristic of an overcurrent relay shown in Fig. 1.

The amount of detail required to represent a relay is determined by the purpose for which its model is to be used. A model based on fundamental frequency phasors may be adequate in some cases, whereas in other cases, the analog electronics and signal flows used in a relay must also be modeled.

Whatever degree of detail is used in a model, the engineer must be aware of the limitations of the model. Failure to bear this in mind is a well-known weakness in all design studies based on models.

All models are intended for checking the performance of relays when inputs of a specified nature are applied. The most commonly used inputs have been the fundamental frequency components of currents and voltages. The models implement the process of substituting the values of the inputs in the equations and calculating the results to determine the performance of the relay. Initially, manufacturers used models of this kind for determining if the performance of their relays would be acceptable or not. Characteristics of overcurrent relays were the first to be modeled. Mathematical models [1], [2] were developed in the form of algebraic equations for representing time-current characteristics of overcurrent relays and later, those equations were used for designing overcurrent relays including a reset characteristic.

Modeling and testing of distance relays has also been reported in the literature. These models were developed by manufacturers for investigating new designs and were used by utility engineers for testing existing relays. One such study [10] modeled mho

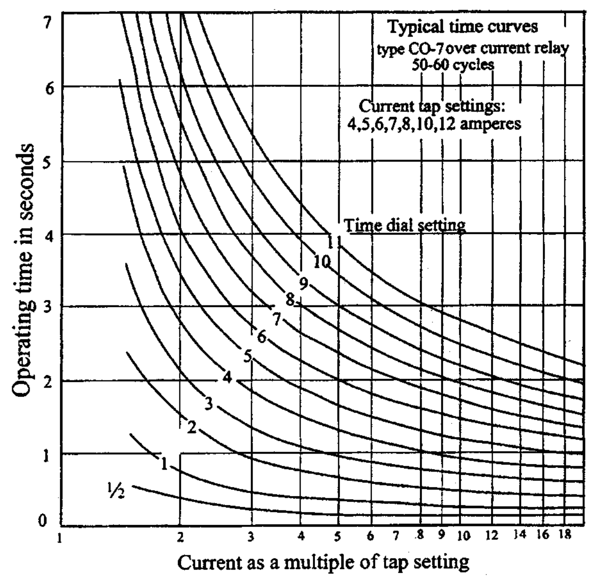

Fig. 1. Typical over-current relay timing characteristics.

elements of distance relays for studying the effect of the type of polarization on the directionality of the relays and for verifying the performance of the relays during specific operating conditions. Other studies developed models and used them for developing an improved method for testing voltage polarized mho relays [3], [4] and yet another study [5] developed a state-space model of an electromechanical distance relay for studying the transient behavior of the relay.

Phasor based models were the first to be widely used by industry and academics to design relays and check their performance. Subsequent work was on the development of "transient" models of relays; some of this work has been reported in the literature [6], [13], [14], [27]. These models take into account the presence of high frequency and DC components in the relay inputs. Because the objectives for developing different transient models are not identical, the complexity of the models varies substantially. It is also important to realize that it is easier to develop transient models for computer-based relays than for electromechanical and solid-state relays.

Both phasor-based and transient models of relays have proved to be useful tools for testing relays and for conducting a variety of protection and system studies [7], [8]. Substantial activity is taking place in this area at this time.

Presently, several software packages are commercially available. These packages provide software models of protective relays and perform fault analysis of the power system. Some of these packages are described in Section III-A.

Manuscript received May 5, 2000.

The authors are with the Working Group C1 of the Systems Protection subcommittee of the PSRC.

Publisher Item Identifier S 0885-8977(01)01547-3.

Considering the importance of the subject of relay modeling, the IEEE Power System Relaying Committee formed a Working Group and assigned it the task of

- reviewing the present state of the art of this area, and
- recommending guidelines for further work in this area.

This paper is the result of the work done by the Working Group and represents the views of its members. The paper provides some background information relevant to relay modeling. It then describes the types of relay model which are in common use. These include generic models and detailed models. The information required for building a relay model and validating it are then given. Finally, summaries of the current uses and future uses of relay models are included.

II. Background Information

Relay engineers are familiar with the traditional method for setting overcurrent time graded protection systems. A "Software model" for such a relay takes the form of equations which represent the set of time-current curves shown in Fig. 1. This model in graphical form is available from the manufacturer and can be easily validated using a relay test set. The user would input the rms fault current in multiples of tap setting and the time dial setting to find the operating time of the relay.

While the model of Fig. 1 is widely used for relay application and setting studies, a considerable amount of information cannot be determined from it. For instance the response of the relay to the following effects cannot be readily determined:

1) Change in fault current after the relay has started to operate (such as in the case of an evolving fault).
2) Transient DC offset, when it is significant. For example, at high multiples of pickup, if the time dial setting is small, the operating time of the relay can be in the same region as the time constant of the transient DC component.
3) Harmonics and off nominal frequency currents.
4) In the case of electromechanical relays, disk inertia and contact bounce and wipe.

Additional models of varying degrees of complexity are required to investigate the various concerns listed above. The simplest model, which represents the transient behavior of a time overcurrent relay, is provided in reference [9]. A transient model of a time overcurrent relay calculates the degree of progress toward the trip level at each instant in time for the specific current at that time. The progress toward trip (or reset) is obtained by integrating the relay current over the period of interest to determine relay response. This type of model is useful for investigating the effect of changing magnitudes of current as noted in item 1 above.

The dynamic model used in Reference [2] determines the response to the fundamental frequency (phasor) currents only. A more complex model is required to investigate the effects noted in items 2 to 4 above. The more complex model would include models of filters and response of the relay over the full frequency spectrum of interest. The most complex model of all would be required to determine the effects of the electromechanical components noted in item 4 above. Some of the significant effects, such as contact condition and electrical loading, will vary from relay to relay or from application to application and are therefore extremely difficult to model accurately. It is important to balance the amount of effort required to develop and validate a model with the amount of effort required to test the relay directly to investigate certain effects.

The vast majority of models in current use employ algorithms based on phasor values.

III. Phasor Models

The fundamental frequency simulations and models are helpful for many applications. Phasor-based models can be used, among others, for the following purposes.

1) Time graded overcurrent curves (Fig. 1).
2) The level setting of an instantaneous relay.
3) The characteristic of a directional overcurrent relay represented by current and voltage phasors plotted on the complex plane.
4) The characteristic of a power relay plotted on the PQ plane.
5) The characteristic of a percentage restrained differential relay plotted as differential current versus restraint current.

Although the above listed phasor models are often plotted on paper, they can be developed into software models by translating their characteristics into equations in a computer program. The use of a software phasor model to represent relay characteristics is helpful to investigate the change in characteristics with changes in other parameters. For example, the minimum operating current of a directional function may vary with the magnitude of the polarizing voltage.

The phasor models of "instantaneous" relays do not give any indication of time response. In time delayed relays, where time is one of the measured quantities (as with a time overcurrent relay) it is usually fairly simple to model the time response. The dynamic model of a time overcurrent relay [2] is one example of such a model. Although the dynamic model is simple, it is very important to ensure that it accurately represents the performance of the actual relay. In particular, any integrating action over time, such as is provided by an induction disk or its electronic equivalent, must be considered in model development [9].

The primary limitation of most phasor models is their inability to handle time-related consequences affecting fundamental frequency phasors. These time related consequences include the effects of DC offset, nonlinearities of CTs and CVTs, and protective relay memory circuits losing stored voltage or current data. Other effects are listed in Section IV.

In spite of their limitations in representing time response, software phasor models do provide an important benefit which is common to all models. They provide the ability to observe (usually by means of graphical plots) the boundary of relay operation on the same diagram as the actual (steady state) parameters which are calculated by the relay. The ability to observe the margin between the boundary of operation and the calculated parameters is very helpful in developing reliable protection applications and settings.

A. Commercially Available Software

Commercially available software programs are mostly interactive with the user and present information in graphical form. They calculate relay responses to RMS values of the steady state fundamental frequency phasors, mathematical models of the network and power system components. The accuracy of the mathematical system models emphasizes the fundamental frequency response, presumes steady state conditions and ideal components but excludes time related consequences. A full range of the network components as well as phenomena, such as distributed zero-sequence mutual couplings and shunt admittances, can be modeled. Fault types, with and without fault resistance, as well as "cross-country" faults can be specified anywhere in the system. Internal network component faults, such as turn-to-turn transformer or generator faults are not usually included. The accuracy of the solutions provided by these software packages is generally dictated by the degree to which the user chooses to model the network being investigated.

The relay models in these software packages assume that the relays operate at the instant when the phasor equations are satisfied and the time equal to the selected time-delay, if any, has expired. These programs have built up large data banks of relays and are in widespread use at the distribution and sub-transmission levels.

The softwares also include phasor models of distance relays. The transient performance of the primary distance protection is not modeled. The models consist of the phasor equations used by the measurement element of the relay. In the case of memory polarized relays, it is necessary to have some prefault conditions established for long enough to prime the relay. Some, but not all [12], commercial software packages may have problems in displaying the characteristics of cross and memory polarized relays because the shapes of the operating characteristics change dynamically during faults depending on the system impedances. Nonetheless the correct steady state operation of the polarized relays is modeled.

B. Distance Relay Models

Fundamental frequency phasor models can, when used appropriately, provide useful information on the response of relays. Phasor models are especially useful in evaluating the response of distance relay mho elements in various applications. An example of such a study is presented in reference [10] which discusses the directionality of distance relay elements as a function of the type of polarization and the prefault line loading.

The standard mathematical approach for analyzing the steady state behavior of phase and amplitude comparators is to define two phasors $\mathbf{S1}$ and $\mathbf{S2}$ as follows

$$\begin{aligned}\mathbf{S_1} &= \mathbf{I_r Z_R} - \mathbf{K_1 V_r}\\ \mathbf{S_2} &= \mathbf{K_2 V_r} + \mathbf{K_3 I_r Z_R} + \mathbf{K_4 V_{pol}}\end{aligned}$$

where:

$\mathbf{S_1}$	is the phasor of operating voltage,
$\mathbf{S_2}$	is the phasor of polarization voltage,
$\mathbf{I_r}$	is the current of a particular fault loop,
$\mathbf{V_r}$	is the voltage of a particular impedance loop,
$\mathbf{Z_R}$	is the reach of the mho detector,
$\mathbf{V_{pol}}$	is the memory or cross polarization voltage, and
$\mathbf{K_1}$, $\mathbf{K_2}$, $\mathbf{K_3}$ and $\mathbf{K_4}$	are complex constants chosen to define the operating characteristic.

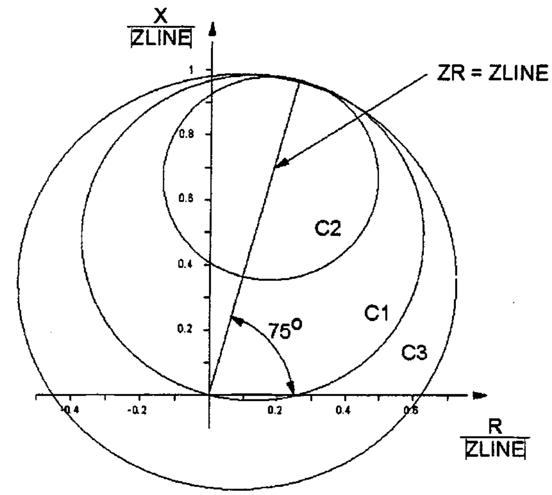

Fig. 2. Mho circles corresponding to various types of polarization and fault direction.

The operating circles and lines can be derived by imposing phase or amplitude constraints on the ratio $\mathbf{S_1}/\mathbf{S_2} = A\angle\theta$. The most familiar constraint is the mho circle enforced by the phase angle limits

$$-\pi/2 \leq \theta \leq \pi/2.$$

If $\mathbf{K_1}$ and $\mathbf{K_2}$ are selected to be unity and $\mathbf{K_3}$ is set to zero, the resulting operating circles take the form shown in Fig. 2. C1 is the self-polarized characteristic, C3 is the expanded forward fault characteristic and C2 is the contracted characteristic for reverse faults. The exact size of C2 and C3 depends on the type of polarization, the value of K4 and the system impedances, but all characteristics pass through the reach point $\mathbf{Z_R}$.

By modeling the mho relay by the above equations and characteristics, it is possible to achieve useful results in complex situations such as the series compensated case shown in Fig. 3. The study [11] showed that with steady state fault signals the relays R1 to R6 had directionality problems. There was no need to conduct transient tests to verify this. On the other hand replacement relays had to be evaluated with both steady state and transient waveforms to ensure that there were no problems in either state.

Since no validated transient model of the relays was available, the transient tests were carried out using a real time system simulator and the actual relays.

IV. Transient Models

Given the fact that when protecting a complex network, a relay may operate before the steady state is reached, a model of a relay should be such that its behavior in the transient state

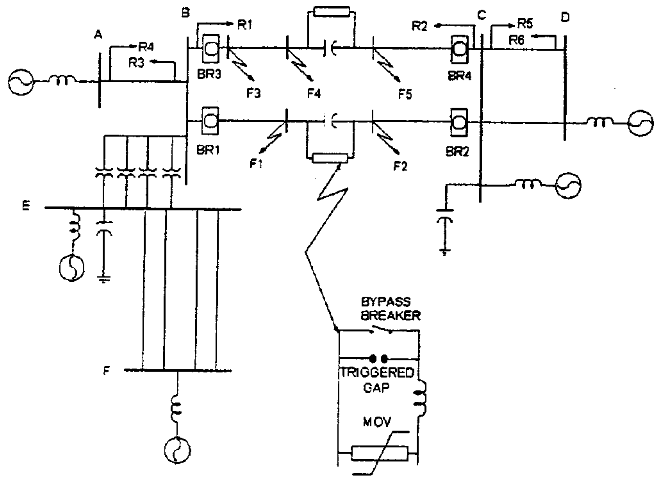

Fig. 3. Reduced system around series compensated lines used to determine suitability of relays R1 to R6.

is the same as the real product. Such situations require transient models for their proper off-line evaluation.

Models of relays which make decisions within two or three periods of the fundamental frequency, must take into account the presence of the transient components in the inputs. For example, dc offset components are present in fault currents and voltages which are applied to relays. To ensure proper transient performance, relay manufacturers and users have frequently performed expensive and time consuming tests which consist of injecting relays with analog signals which may be encountered in actual service [7]. If software models which properly reproduce the transient performance of relays were available, the test signals in numerical form could be applied to the model thereby avoiding the need to convert the signals to analog form, amplify them, and make wire connections to the physical relay and monitoring equipment. Therefore "software" models reduce the degree, and the associated expense of, pre- and post-application testing with signals of different levels of complexity. Another advantage of "software" models is that the internal processes of relays can be examined and charted over the course of any event of interest. This means that instead of the simple "trip" or "no trip" result of a test, the model provides information on the margins associated with the actual response [8], [13].

In the absence of appropriate transient models, such system conditions can only be investigated by using a power system simulator which is able to produce the system transients.

Some of the situations which require transient models for proper evaluation are

1) transformer or capacitor inrush,
2) ct or cvt transient,
3) ct steady state saturation,
4) presence of harmonics,
5) presence of transient DC offset,
6) evolving faults,
7) power system swings and dynamics of rotating machines,
8) time varying machine impedances (from sub-transient through transient to steady state),

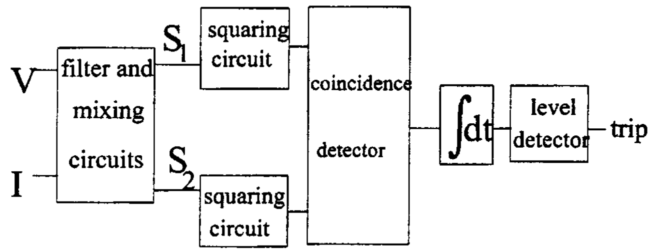

Fig. 4. Block Diagram of block-average phase comparator.

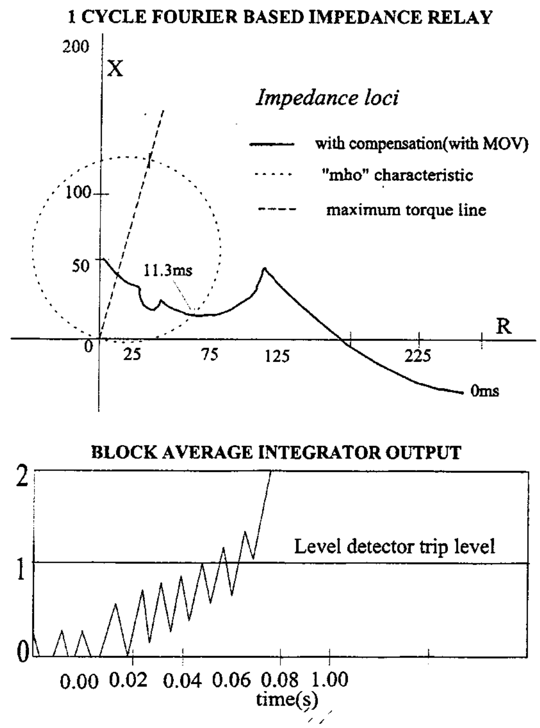

Fig. 5. Transient Z trajectory and block average response.

9) one line to ground faults on resonant grounded systems,
10) and series capacitors and their protection.

A. Generic Models

If the operating principle of the measuring element is known, then a generic model can be used [13], [25]. For instance, if the relay is known to be a mho phase comparator type using a block average integrating function then a generic relay with a block diagram as shown in Fig. 4 may be used. The exact details of any filters or mixing circuit elements may not be necessary as long as the phasor relationships in **S1** and **S2** are correct at fundamental frequency.

If on the other hand, the relay operates on a one cycle Discrete Fourier Transform and divides V by I to get a transient value of Z then this function can be set up as an equation. Fig. 5 shows the results for these two relay types taken from a series compensation study [13]. The line, which the relay is protecting, is mid-compensated and the fault is just beyond the compensation. The characteristic of the self-polarized mho relay and the trajectory of the transient values of Z are shown on the impedance plane at the top of Fig. 5. MOV action across the series capacitor makes the measured impedance fairly resistive until the MOV bypasses at about 60 ms into the fault. The integrator on the block average phase comparator does not develop an upward trend until 11.3 ms when the impedance trajectory comes inside the mho characteristic. Thereafter, it ramps up slowly as the measured impedance remains close to the operating boundary. Once the bypass closes at 60 ms (at the cusp inside the characteristic) the ramp builds up rapidly to its upper level. This is consistent with the fact that the impedance has now moved into the middle of the characteristic. The operating time for the phase comparator is around 40 ms but this may not be precise if the model is not exact. However, this has provided some insight into what the relay was doing other than just seeing a trip signal at around 40 ms. This insight indicates that some form of polarization which increases the transient resistive reach for forward faults (see Fig. 2) would speed up the operating time of the phase comparator.

Generic models are easy to set up, give considerable insight into the operation of the relay type but may not be suitable for marginal cases and precise timing. They may not have detailed logic provided in specific implementation of the generic principle in a specific relay. This logic is often applied to make specific functions interact with other functions to make a protection system. Because of this limitation, generic models find best use for checking specific functions, rather than complete systems which are made up of numerous interacting functions. Also, because of this limitation, they are less useful (than detailed models) for investigating unexpected relay operations where model specific details are often important

B. Detailed Models

Detailed models preserve all of the advantages of being able to examine the internal operation of any function. The detailed models are more useful (than generic models) for checking the performance of complete systems because all logic is represented. Unfortunately, detailed models are not as readily available as the generic models because they may include trade secrets of the manufacturers. The manufacturers may be prepared to provide such models as “black boxes” with specific, fixed interfaces, e.g., in MATLAB.

A manufacturer is in a position to design a fairly accurate model particularly for the new digital relays. (As explained in Section V the software model may precede the hardware design.) The analog front end is the only part which requires translation into software form although there may be some timing and numerical issues with regard to completion of specific calculations in the digital hardware (see Section IV-C)

Where the algorithms and hardware are known in detail very precise performance can be achieved in the model. Reference [14] presents a comparison of the trajectories of the transient values of Z calculated by a relay and calculated by the model of the same relay. The model was a Fortran subroutine running in an EMTP (EMTDC). Precise timing is available from such a model if required for use in off-line studies involving accurate models of other high speed controllers to examine any interactive effects. The alternative to such an off-line study would be to have the actual relay and other controllers linked to a real time simulator. This is not an option available to most relay engineers.

C. Hardware Modeling

The algorithms in a digital relay can be translated from machine code into whatever language is being used in the model. As explained previously, modeling the analog parts of any relay requires care although the front end of digital relays can be dealt with in a fairly straightforward manner in all but a few cases where the auxiliary transducers may saturate.

There are issues of timing, dynamic range and number of bits in digital hardware which should be examined [15], [26].

Current and Voltage Acquisition System Characteristics: A number of characteristics pertaining to the analog acquisition system are important when trying to set up a model for a relay. They are:

- the maximum value of measurable instantaneous voltage and current and
- the least value of the measurable instantaneous voltage and current often also called the resolution of the measuring system.

The ratio of the above two quantities determines the dynamic range of the relay with respect to voltages and currents.

There exist situations where a relay’s simulation could be affected by an improper simulation of the characteristics of the data acquisition system. Two examples are as follows.

1) The model is used in a study in which the maximum value of fault current is more than the maximum current which can be measured by the data acquisition system and the saturation of this system is not modeled.
2) The model is used to implement thresholds which are below the combined accuracy of the analog acquisition system and the analog-to-digital converters. An example of this situation is the implementation of the anti-motoring function in a generator in which the power thresholds used are exceedingly low.

A relay model may, therefore, perform differently than the real relay if the errors, nonlinearities and dynamic range issues are not dealt with properly.

Numbers Representation Issue: Ideally, numbers at different stages of processing (both hardware and software) should be represented in a model as in the real world. This constraint is not always easy to meet.

The numbers provided by analog-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 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. Processing in the floating-point format has a limited impact on the overall accuracy.

V. Information Required for Models

The development of a software model is relatively simple for digital relays provided sufficient information on the algorithms is available. For static and electromechanical relays, and indeed for the analog sections of digital relays, the detailed modeling problem is nontrivial. Electro-mechanical relays are particularly difficult to model because detailed knowledge of the mechanical design is needed. In such a case, it might be impractical to develop a sufficiently detailed model.

As a general rule, to be able to develop the model of a digital relay, the manufacturer should provide information concerning the basic principles which are used by the relay while processing data generated by acquiring the signals and making decisions.

Most designs of modern relays are based on the simulation of the relays using packages like MATLAB. These simulation tools are used by the manufacturer at the development level to assess the reliability and soundness of the algorithms using voltage and current waveforms of faults simulated on programs like an EMTP. Once that step in the development process has turned out successfully, the simulation software is converted to 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. The manufacturer could make such a model available for use by the engineers of the utilities and consultants. Such a model will only allow evaluation of the *functionality of the protection algorithms* in different fault situations for different networks. Evaluation of the model is not a proper test for testing the relay itself. For instance a faulty chip in the relay will not be detected when evaluating the model. Nor will any real time effects due to the time the hardware needs to run the coded algorithms come to light.

To model a relay properly, all the elements or ingredients which determine the dynamics of the relay in the transient state have to be properly simulated. Therefore, all the information required to allow an engineer to model these elements should be available from the manufacturer.

A. Conventional Sources of Information

Conventional sources of information on the technology of digital relays consist of the following documents:

1) Papers in general, textbooks on relaying and digital relays and IEEE special publications [16]–[18], [23], [24]. Most relaying principles belong to the public domain and in most industrial products, so-called proprietary information is usually minimal.
2) Papers written by the designers of relays or manufacturers representatives. The quality and the amount of information found in these papers depends very much upon the will of the manufacturer to reveal or to hide the basic facts of relays [19]–[21].
3) Patents taken out by the manufacturer, if any. This is very often the most detailed source of information.
4) The relay manuals published by the manufacturer. Most of the time the "logic diagram of a protection scheme" is available in these manuals.
5) Direct contacts with the manufacturer.

B. Useful Information

Information on the following topics will be useful when trying to develop the model of a relay.

1) Basic Characteristics of the Digital System: A number of characteristics are common, although not necessarily identical, to all digital systems. The following items are described in the manufacturer's data sheet.

Nature and Cut-Off Frequency of the Anti-Aliasing Filter: Ideally the anti-aliasing filter should be defined by its transfer function. If it belongs to a well-documented category of filters, it could be defined in general terms, for instance "fourth order Butterworth filter with a cut-off frequency of 480 Hz." If the electronic schematic of the filter and parameters of the components are available, its transfer function can be computed by analyzing the diagram.

Primary Sampling Rate and Relay's Sampling Rate: Many of the newest generation of relays use an over-sampling technique. The high sampling rate is used for oscillography. An analog anti-aliasing filter precedes the sampling of signals. The data used by the relay in its algorithms is obtained after decimation of the data acquired at high sampling frequency. The decimation process includes a second digital anti-aliasing filter implemented in software. The digital transfer function of this anti-aliasing filter is also needed. The high sampling rate would typically be 64 samples per cycle and the relay algorithm might use 16 or 8 samples per cycle.

For most digital relays at present in service both rates are the same. This means that we end up with a single sampling frequency and a single analog anti-aliasing filter.

2) Phasor Estimation Algorithm: Most digital relays estimate amplitudes and phase angles of phasors using digital filters.

Algorithms for estimating phasors is one of the most documented topics in the field of digital protection [16], [23]. In spite of the wide range of potential candidates for that purpose, a limited number of algorithms have been used in commercial applications. The full-cycle Fourier filter and the so-called Cosine filter are the most common and have become *de-facto* standards in the industry [22].

Given the extensive amount of documentation available to the relay engineer on the filtering algorithms, a manufacturer would only have to point to the filtering system used by its name. For instance characterizing a filter as "a full-cycle recursive Fourier filter" tells all about the filter's nature and reconstruction for a model is straightforward.

3) Additional Functions: Most modern digital line relays use a technique of frequency tracking, the purpose of which is to render the relay insensitive to frequency excursions. In line relaying, frequency tracking has a direct impact on the memory voltage used in the polarization of a mho element. In most cases the frequency tracking is achieved with a phase locked loop circuit implemented in analog hardware.

A number of additional functions like directional elements, detection of power-swing, computation of sequence quantities, phase selection logic etc. would normally need to be modeled. The same principles apply to these functions: basic description of their algorithms should be obtained.

Algorithms Based on Something Other than Phasors: Although the use of phasor evaluation has become an almost standard practice in line relays, other algorithms exist.

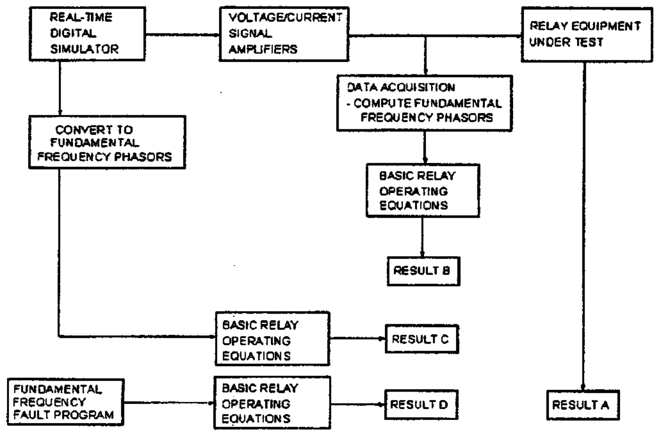

Fig. 6. Development and validation of relay models.

For example some algorithms are based on the digital simulation of the differential equation representing a line when others are based on the digital simulation [21] of an electromechanical cylinder unit performing the task of phase comparison.

Whatever the technique used, the model will have to reproduce the proper dynamics in order to exhibit the same outputs during transient state.

VI. Model Validation

As with any other model to be used in computer simulations, the model needs to be proved by comparison with real-life performance of the relay. This has become relatively simple to achieve with the widespread availability of playback relay test sets and real time simulators. Engineers can now input identical waveforms to both the relay and the model and compare performance in order to validate the model.

A. Validation of Phasor Models

Although phasor models are relatively simple compared to full transient models of relays, the verification of the models for reasonable confidence level requires a certain amount of care and effort Fig. 6 shows a process which has been developed by a Utility for the development and verification of relay models. It involves the comparison of the results from various sources, including the results from the equipment. under test (Result A), and results from response of the basic operating equations as computed from: i) the signals applied to the relay (Result B); ii) the fundamental frequency phasors obtained from digital simulation (Result C); iii) the fundamental frequency phasors obtained from a fundamental frequency fault program (Result D). This arrangement has the feature of cross-checking the various sources of data, and gives credence to results from a simple fault program which can be used for quick assessments to zero-in on critical cases.

B. Validation of Transient Models

The transient model will either be available from a manufacturer or will involve considerable modeling effort from the relay engineer. Once acquired it must be validated as in Section VI-A by applying identical transient waveforms to both the relay model and the relay and comparing results [14].

VII. Uses of Models

In Section III, it is shown that phasor models are used in commercially available software packages for choosing appropriate settings for the steady state operation of overcurrent relays and distance relays. This is presently the most familiar use of relay models.

By using relay transient models the application engineer can do “first cut” selection of different types of relays as candidates for full transient tests using the actual relay. Typical questions which might be addressed are as follows. Do we need memory polarization or cross polarization, or a bit of both? Is a phase comparator better than an amplitude comparator algorithm? Will the polarization be suitable in a series compensation application? How close does the relay come to operating for a fault behind its busbar or just beyond the remote busbar? How does the measuring technique respond to a sudden phase reversal of current or voltage as a circuit breaker opens or an MOV bypasses? Once such issues have been resolved the relay engineer can proceed to more detailed testing of actual relays using a simulator or test set. Off-line simulations are less expensive than on-line real time testing and should be used to settle the broader issues, such as those mentioned above, leaving only the detailed performance of a particular relay for on-line testing.

In whatever mode the models are used they will distinguish between inherently good or inherently bad performance. The model allows the engineer to examine the outputs from various intermediate points within the relay and not just at its output terminals (See Fig. 5). As such it has considerable training benefits in understanding the operation of the relay and it further allows margins of operation to be evaluated.

Significant savings in troubleshooting costs are presently being realized by utilities using “software” models to analyze unexpected relay behavior. Instead of dispatching a technician or engineer with test equipment to perform time consuming diagnostic testing after an unexpected relay behavior is identified, current and voltage phasor data from the event is retrieved via a communication link. The source of these phasor values ranges from digital disturbance recorders, which provide data using very high sampling rates, to the fundamental frequency current and voltage phasor signals recorded by the protective relays. After the phasor data has been downloaded from the substation the values are subsequently applied to the relay’s software model to confirm or refute the operation in question.

If the result of the “software” model evaluation of the event agrees with the actual behavior of the relay, the focus of the investigation shifts to confirming the appropriateness of the relay application. Should the “software” model analysis contradict the actual operation of the relay, diagnostic testing of the relay or relay replacement is performed with greater certainty that the relay is faulty and not misapplied.

VIII. Future Uses of Models

With the growing use of electromagnetic transients programs for system studies there is sometimes a need to include transient relay models, generic or specific, in the studies. Systems engineers are interested in the interaction between the system and its control apparatus (the relay is one such controller) and relay engineers need to look beyond the response of the first relay operation. The behavior of control apparatus for FACTS devices or other fast acting controllers is influenced by the timing of fault clearing and, where appropriate, reclosing, and such events must be properly modeled in the study. There is little point in having an accurate model for the FACTS controller without an equally good model of the relay, recloser and breaker. In addition, with operating margins being cut to the minimum, we are seeing more "downstream" effects of system disturbances which take place after the first correct protection operation, e.g., the mal-operation of relays on a parallel line following the correct opening of the breakers on the adjacent line. To deal with such situations requires interactive testing with real time simulators and relays, or off-line studies including accurate models. Even when a real time simulator is being used to test a single relay or controller in interactive mode the other relays and controllers must be modeled on the simulator to allow complete system testing.

IX. Conclusion

Software phasor type models are already in widespread use by relay engineers. Software transient models, generic or detailed, are increasingly being used by Utilities to examine difficult application issues. The information on which such models is based is either available from manufacturers, from manufacturers leaflets or patents, or from technical papers describing the relay performance. Software models must be validated against the performance of the actual relay and the relay engineer must be careful to use the model only in situations where any assumptions on which the model is based, are applicable.

References

[1] J. Singh, M. S. Sachdev, R. J. Fleming, and A. E. Krause, "Digital IDTM overcurrent relays," in *Proceedings of IEE 1980 DPSP Conference*, IEE Publication no. 185, pp. 84–87.

[2] E. O. Schweitzer and A. Aliaga, "Digital programmable time-parameter relay offers versatility and accuracy," *IEEE Trans. on Power Apparatus and Systems*, vol. PAS-89, no. 1, pp. 152–157, Jan./Feb. 1980.

[3] W. O. Kennedy, B. J. Gruell, C. H. Shih, and L. Yee, "Five years experience with a new method of testing cross and quadrature polarized relays—Part I: Results and observations," *IEEE Trans. on Power Delivery*, vol. 3, no. 3, pp. 880–886, July 1988.

[4] ——, "Five years experience with a new method of testing cross and quadrature polarized relays—Part II: Three case studies," *IEEE Trans. on Power Delivery*, vol. 3, no. 3, pp. 887–893, July 1988.

[5] Z. Peng, M. S. Li, G. V. Wu, T. C. Cheng, and T. S. Ning, "A dynamic state space model of a MHO distance relay," *IEEE Trans. on Power Apparatus and Systems*, vol. PAS-104, no. 12, pp. 3558–3564, 1985.

[6] T. S. Sidhu, M. Hfuda, and M.S. Sachdev, "Generating relay models for protection studies," *IEEE Computer Applications in Power*, vol. 11, no. 4, pp. 33–38, Oct. 1998.

[7] "IEEE Committee report 'relay performance testing',", IEEE Special Publication no. 96 TP 115-0, 1996.

[8] J. B. Mooney, D. Hau, F. Plumptre, and C. Henville, "Computer models simplify relay application studies," in *Western Protective Relay Conference*, Spokane, Oct. 1993.

[9] *Standard for Time Overcurrent Relay Characteristics*, ANSI/IEEE Standard C37.112 1997.

[10] R. J. Marttila, "Directionnal characteristics of distance relay Mho elements—Part I: A new method of analysis," *IEEE Trans. on PAS*, vol. PAS-100, no. 1, Jan. 1981.

[11] ——, "Evaluation and testing of line protections for series compensated transmission lines," in *IEE DPSP 97 Proceedings*, IEE Conference Publication No. 434.

[12] L. P. Cavero, "Computer aided evaluation and application of distance relays," in *IEE DPSP 93 Proceedings*, IEE Conference Publication no. 368.

[13] J. R. Lucas and P. G. McLaren, "Some problems in relaying series compensated lines," in *Proceedings of IEEE CCECE Conference*, Sept. 1990, p. 1.1.1.

[14] P. G. McLaren, E. N. Dirks, R. P. Jayasinghe, G. W. Swift, and Z. Zhang, "Using a real time digital simulator to develop an accurate model of a digital relay," in *Proceedings of ICDS '95*, College Station, TX, USA.

[15] T. S. Sidhu, M. S. Sachdev, and H. C. Wood, "A computer-aided design tool for developing digital controllers and relays," *IEEE Trans. on Industry Applications*, vol. 28, no. 6, pp. 1376–1383, Nov./Dec. 1992.

[16] A. G. Phadke and J. S. Thorp, *Computer Relaying for Power Systems*: Research Study Press Ltd., John Wiley & Sons Inc., 1988.

[17] V. Cook, *Analysis of Distance Protection*: Research Study Press Ltd., John Wiley & Sons Inc., 1985.

[18] M. S. Sachdev (Coordinator), "Computer relaying," IEEE Tutorial Course Text, Publication no. 79 EH0148-7-PWR, 1979.

[19] F. Engler, O. E. Lanz, M. Haggli, and G. Bacchini, "Transient signals and their processing in ultra high-speed directional relay for EHV/UHV transmission line protection," *IEEE Trans. on Power Apparatus and Systems*, vol. PAS-104, pp. 1463–1473, June 1985.

[20] E. O. Schweitzer and J. Roberts III, "Distance relay element design," in *19th Annual Western Protective Relay Conference*, Spokane, WA, Oct. 20–22, 1992.

[21] D. Hart, D. Novosel, F. Calero, E. Udren, and L. Yang, "Development of a numerical comparator for protective relaying—Part II," *IEEE Trans. on Power Delivery*, vol. 11, no. 3, pp. 1274–1284, July 1996.

[22] G. Benmouyal, "Removal of DC-offset in current waveform using digital mimic filtering," *IEEE Trans. on Power Delivery*, vol. 10, no. 2, pp. 621–628, Apr. 1995.

[23] "Microprocessor relays and protection systems," IEEE Tutorial Course Text, Publication No 88EHO269-1-PWR.

[24] "Advancements in microprocessor based protection and communication," IEEE Tutorial Course Text, Publication no. 97TP120-0, 1997.

[25] M. S. Sachdev, M. Nagpal, and T. Adu, "Interactive software for evaluating and teaching digital relaying algorithms," *IEEE Trans. on Power Systems*, vol. 5, no. 1, pp. 346–352, Feb. 1990.

[26] H. C. Wood, M. S. Sachdev, and T. S. Sidhu, "Tools for computer aided development of microprocessor based power system relays," in *Proceedings of the IEEE IAS 1987 Conference*, 1987, Publication no. 87CH2499-2, pp. 1733–1737.

[27] M. Kesunovic and Q. Chen, "A novel approach for interactive protective system simulation," *IEEE Trans. on Power Systems*, vol. 12, no. 2, pp. 668–694, Apr. 1997.