DIGITAL SIMULATION OF POWER SYSTEM PROTECTION UNDER TRANSIENT CONDITIONS

by

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ABSTRACT

This work demonstrates the use of digital simulation for analyzing protection system performance. For studies of complex, multi-relay protection systems, digital simulation provides utility engineers with an attractive alternative to relay testing techniques. The cost of digital simulation facilities can be lower than the cost of comparable testing facilities; relay hardware does not have to be made available for the test laboratory.

Digital simulation would ordinarily be impractical for security and dependability studies, due to the thousands of individual simulations involved. The number of simulations needed can be greatly reduced by using a technique called "numerical logic replacement" for implementing the protection scheme logic. This unconventional technique makes near-misoperation visible from individual simulations. The likelihood of overlooking potential misoperation is thus much lower than with the usual direct (Boolean) implementations.

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CHAPTER I. INTRODUCTION

Power system response to faults and other sudden disturbances includes both "transient" and "steady-state" components. For low-speed protection systems, the transient component is generally ignored; only the steady-state component is used for analysis. For high-speed protection systems, the transient component must be considered as well, since it creates a serious risk to protection security and dependability.†

Sudden changes in power system voltages and currents produce "transient" and "steady-state" components in the relay and instrument transformer responses also. Both of these components must be considered for studies of high-speed protection systems.

The complete response (i.e. accounting for all transient and steady-state components) of a protection system is usually determined using sophisticated relay test facilities. These facilities simulate protection response to a disturbance, using analog or digital techniques for modelling the power system, and actual relays for the protection system.

While relay test facilities are the most accurate (laboratory) method for determining the responses of individual relays, they have three practical disadvantages which limit their use by utility protection engineers.

Firstly, test facilities are not readily available. Few utilities could justify the high cost of building, maintaining, and operating a test facility in house. Access to existing external facilities is limited, and too inconvenient except for

†Security deals with the erroneous operation of a relay in the absence of a fault; dependability deals with the failure of a relay to operate when a fault occurs.

special studies (e.g. testing a relay of advanced design in a new and difficult application).

Secondly, by their very nature test facilities require the relays to be physically on site. This makes it difficult, if not impossible, to use such facilities for the evaluation of conceptual protection schemes, where the relays to be used may exist only in prototype form, if at all. Even the analysis of existing protection systems can be difficult, since enough spare relays must be collected to duplicate the protection in the laboratory.

Further, relay test facilities are generally quite limited in the number of relays which can be handled simultaneously. This complicates the evaluation of complete protection schemes, which are usually of more concern to utilities than one or two principal relays. Only by studying the performance of the complete protection scheme is it possible to account for the effects of the scheme logic on dependability and security.

The research described in this thesis explores the use of digital simulation techniques, as an alternative to relay testing, for predicting complete protection system response. Digital simulation is free of the three disadvantages of test facilities listed above. As a result, it better addresses the (non-testing) needs of the utility protection engineer.

Previous use of digital simulation has been limited to single relays, or to simple combinations of a few relays, such as underreaching transfer-trip schemes for transmission lines. The research described herein successfully applies digital techniques to the simulation of a large, multi-relay protection scheme used by the British Columbia Hydro and Power Authority (B.C. Hydro).

Two major restrictions to the wide-spread application of digital simulation are the lack of suitable industrial-grade protection simulation programs, and the high cost of the many simulations needed to reliably establish protection security and dependability. The latter problem is addressed in this research by using an unconventional technique, herein called "numerical logic replacement" (NLR, described in chapter III) to implement the protection scheme logic.

NLR provides a numerical measure of how "close" the protection comes to operating during a simulation. This is a major advance over the direct implementation, using Boolean logic, employed for conventional digital and analog simulations. Direct implementations indicate only whether or not the protection operates. No warning is given of near-operation, or more importantly, near-misoperation. NLR provides this warning.

The numerical measure of "nearness to operation" provided by NLR not only greatly reduces the likelihood of overlooking potential misoperation, it also provides a direct "index of misoperating tendency". This "index" can be used to identify changes in simulation parameters which increase the risk of misoperation. The operator, or even the computer itself in an automatic mode, can then select only simulations which produce a high risk of misoperation. The number of simulations required to prove protection security and dependability is thus greatly reduced, as is the total simulation time and cost.

In order to carry out this research, it was necessary to develop a protection simulator. This provided an excellent opportunity to explore the requirements of an industrial-grade simulator. Flexibility, ease of use, a wide range of features, the ability to handle large protection schemes, ease of adding user-written relay models, and portability were characteristics which would clearly be required. The simulator produced for this research incorporates these features.

Along the same lines, the need to develop a large variety of relay models provided an opportunity to test modelling approaches which would be useful for industrial protection simulation. It was obvious that exact models would not be required for all relays. The less-important relays (e.g. some supervisory relays, relays used for local backup protection, etc.) would require only "generic" models. Generic models share the same general principles of operation as the actual relays (e.g. overcurrent relays based on average current measurement), but omit details such as input filtering or input sensitivity levels.

The principal measuring relays in a high-speed protection scheme, in contrast, would require more detailed modelling. This might include the specifics of the input circuitry (e.g. filters), comparator details (e.g. input sensitivity levels), and details of the relay output circuitry (e.g. blocking or latching features); the nature and application of the relay would determine which features were important enough to be included in any specific model.

Exact relay modelling, wherein the behaviour of the actual relay is duplicated as accurately as possible for all plausible operating conditions, was not feasible for this research. Exact modelling requires samples of the actual relays, and extensive access to a sophisticated relay test facility for testing them. The latter, in particular, was not available for this research.

Modelling detail was therefore restricted to information which could be obtained from the manufacturer's instruction manuals. Testing of the models was limited to situations where the operation of the actual relay was known or predictable. As these restrictions would be expected in a typical utility environment, they effectively demonstrated the practical difficulties which utilities would face when preparing relay models.

The remainder of this thesis is organized into six chapters and three appendices. Chapter II discusses transient phenomena which must be considered in protection studies, and the relay test facilities conventionally used to study them.

Chapter III discusses the use of digital simulation, as an alternative to relay test facilities, for studies of complete protection systems. The theory, principles, and procedure for NLR are described in detail.

Chapter IV discusses power system and protection modelling for digital protection simulations. The two methods by which power system and protection simulations can be combined are compared.

Chapter V describes the B.C. Hydro Peace River system and the modelling (in general terms) used for the power system and protection simulations.

Chapter VI describes the results of simulations of the protection for a key transmission line of the B.C. Hydro Peace River system. A number of benchmark simulations are described in detail, and the resulting protection waveforms presented.

Chapter VII summarizes the results of the research, and suggests directions for future work.

Appendix A provides additional detail about the B.C. Hydro Peace River system and the modelling used for the power system simulations.

Appendix B describes the protection modelling in detail.

Appendix C describes the Transient Response Processor (TRP), which was the simulator developed for the protection simulations.

CHAPTER II. TRANSIENT PHENOMENA AND POWER SYSTEM PROTECTION

A. *INTRODUCTION*

Reliability is perhaps the most important requirement of power system protection schemes. The reliability of a protection system is determined both by the reliability of the hardware itself, and the reliability of the "decisions" made by the hardware.

"Decision" reliability, which is usually divided into "security" and "dependability", becomes increasingly difficult to achieve as relay operating speed increases. The short measurement time during high-speed operation reduces the amount of information the relay has available to make its decision. Transients originating in the power system and the instrument transformers are therefore much more disruptive for high-speed relays (operating in 0.5 cycles or less) than for low- or medium-speed relays. For essentially the same reasons, the transient response of the relay measuring circuit is more important for high-speed relays than for slower relays. Consequently, there has been increasing interest in recent years in the behaviour of protective relays under transient conditions.

B. TRANSIENT EFFECTS

1. Problems due to power system transients

There are basically two types of power system transient which cause problems for protection. The most familiar of these is current offset. Offset currents can cause CT (current transformer) saturation, and relay overreaching. Because current offset affects low- and medium-speed relays as well as high-speed relays, it has been widely studied for many years.

The second type of power system transient which can present problems for relays is caused by travelling-wave reflections in transmission networks. Since the resulting high-frequency oscillations generally cause problems only for high-speed relays, travelling-wave reflections attracted little interest prior to the last decade. The most common problem caused by these reflections is delayed operation of distance relays (see, for example, Johns and Aggarwal, 1977). Distance relay inputs are commonly filtered to minimize these delays (Hayden et al., 1971; Souillard, 1978; comments of Suzuki and Chamia during the General Discussion for CIGRE Study Committee 34, 1978; Okamura et al., 1980; Kudo et al., 1985).

2. Problems due to instrument transformer transients

The major cause of transients originating in CTs and CVTs (capacitive voltage transformers) is sudden de-energization of the transformer primary. CTs become largely or completely de-energized when internal or nearby-external faults are cleared; CVTs become largely de-energized during faults close to the CVT location.

In CTs the de-energization transient is a unipolar "current tail", which can have a long decay time constant. This current tail can delay dropout of "low-set" level-detecting current relays.

In CVTs the de-energization transients consist of decaying oscillations of high and low frequency. Although of low amplitude, these oscillations can easily swamp the small power-frequency output during close-up faults. The low-frequency oscillation, in particular, can cause incorrect phase comparison in distance relays, leading to improper operation for faults immediately "behind" the relay.

3. Problems due to relay transient behaviour

The transient behaviour of the relay itself influences decision reliability just as do power system and instrument transformer transients. The transient response of relay input circuitry is one important factor. With memory-polarized mho relays, for example, the expanded "transient" region of the characteristic is affected by the action of the relay input filters. The high-Q input filters delay relay operation, during which time the relay memory decays. This decay causes the transient characteristic to be smaller than simple analysis would predict. (In effect, both phase comparator inputs have "memory".) Because of this interaction, it is essential that memory-polarized relays be evaluated under transient conditions whenever the "transient" reach is to be relied upon.†

The transient response of relay comparators is also an important factor. The operation of electronic "phase comparators", for example, is based on polarity coincidence between the two inputs. The effect of phase comparison is therefore

†Chapter V describes a practical instance of this effect, discovered while testing parameter values for the example simulations.

obtained only for periodic inputs of regular form, such as sinusoids. (This is hardly surprising, since the concept of phase has no meaning except for a periodic waveform.)

For the complex, non-periodic input signals which exist under transient conditions, the comparator output will depend on the comparator operating principle. The so-called "block-average" phase comparator, for example, exhibits less sensitivity to offset currents than does the so-called "block-instantaneous" design (Jackson, 1981).

The behaviour of these two designs in the presence of high-frequency transients (produced by travelling-wave reflections, for example) is also different. The block-instantaneous comparator resets during the resulting short non-coincidence periods; the block-average comparator exhibits a "dithering" behaviour (Johns and Aggarwal, 1977).

C. RELAY TESTING TECHNIQUES

Increasingly over the last decade, the importance of transient effects to the decision reliability of high-speed protection systems has been gaining recognition. This has resulted in increasing use of testing and simulation for evaluating relays and protection systems. According to Chamia and Liberman (closure to discussion, 1978), over 5000 digital and analog simulations were carried out on the ASEA RALDA relay. GE reportedly conducted over 8000 separate fault tests during laboratory testing of a digital protection system (J.T. Tengdin discussion to Chamia and Liberman, 1978).

The most common method of verifying relay behaviour in the presence of transients is through the use of relay test facilities. These facilities are specially designed for observing hardware performance during simulated disturbances. They provide a convenient and practical alternative to field testing using staged faults. The power system voltages and currents are simulated, using either analog or digital techniques, and applied as "synthetic" inputs to the actual relay hardware.

The basic simulation approaches are outlined in the following section. A more complete discussion has been prepared by CIGRE Working Group 34-06 (1980). There is also some excellent discussion on relay testing in the CIGRE Group 34 General Discussion (1980).

1. High- and medium-power analog simulation

The traditional, and simplest, system for simulating a power system for relay testing uses an adjustable, three-phase Thevenin-equivalent "source" network, and inductances to represent the apparatus (e.g. transmission line) being protected. While too crude for comprehensive testing of modern high-speed protection, these "test benches" were very useful for studying the effects of current offset, and for checking the static characteristics of relays.

A significant improvement over the simple test bench is the model power system (or power system simulator), which is better able to account for the dynamics of the power system. The simulator is usually small, consisting of perhaps two synchronous generator sources and two parallel transmission lines (represented by cascaded pi-sections), plus miscellaneous other necessary items (transformers, switches for circuit breakers, etc.).†

Model power systems are in common use by relay manufacturers (comments of Smith, Petrov, and Suzuki during CIGRE Group 34 General

†Some installations are much larger—see the comments by Ogorelec during the CIGRE Group 34 General Discussion (1978).

Discussion, 1978; Hayden et al., 1971; Muller, 1980). They are, however, better suited for studying the effects of medium-term power system dynamics than short-term power system transients. The power system representation used is necessarily approximate, and is not suitable for accurate simulation of travelling-wave effects. This is particularly due to the difficulty of building transmission-line models with wide frequency response at high power levels.

The high power levels result from the practice of driving the relays directly from the model, thus requiring the use of relatively high voltages and currents. Network powers of several hundred kVA are required if actual instrument transformers are to be used between the power system model and the relays under test. Even if lower-power model instrument transformers are to be used, network powers of 50 kVA or more can be required (CIGRE Working Group 34-06, 1980).

A modern alternative is to conduct the simulation at a low power level, and amplify the voltages and currents for application to the relay hardware.

2. Low-power analog simulation

The modelling complexity required for accurate analog simulation of power systems is practical only at low power levels. For use in relay testing, the low-level simulated voltages and currents must be amplified by high-power, high-quality amplifiers before application to the relay inputs.

There are essentially two approaches used for low-power simulation. The first is to construct what is essentially a low-power equivalent of a model power system. This is the approach which has been taken by ASEA (Chamia and Hillström, 1983).

The second approach is to make use of TNAs (transient network analyzers), which are analog devices designed for the highly-accurate simulation of power system transients. The use of TNAs for power system transient simulation is well-established at major TNA sites around the world (e.g. CESI, IREQ), and excellent simulation results can be achieved. For relay testing, the TNA essentially replaces the model power system for the power-system simulation. As with low-power model power systems, the output quantities from the TNA are amplified before application to the relays.

The use of a TNA for relay testing has been described by Lionetto et al. (1980), and has also been mentioned by Schumm (CIGRE Group 34 General Discussion, 1978).

3. Digital computer simulation

Digital computer simulation of the power system is an attractive alternative to the use of low-power analog simulation. Modern digital computer programs, such as the widely-used Bonneville Power Administration (BPA) Electromagnetic Transients Program (EMTP), are available at modest or no cost for use on many popular computers. Only moderate expertise is required for effective use (as opposed to TNAs, for example), and excellent simulation results can be obtained.

Digital simulation offers unexcelled flexibility; changes to base-case simulations may be made quickly and conveniently. This is in marked contrast to model power systems and TNAs. The high cost of simulation time on TNAs, in particular, in most cases requires fault waveforms to be recorded and catalogued for later use. Variations on available fault cases are then inconvenient and expensive to obtain due to the need for repatching. Data files for digital simulation, in contrast, are easily stored for later use, and can be readily modified with a text editor. Subsequent individual simulations are thus relatively inexpensive compared with model power systems or TNAs.

As with low-power model power systems and TNAs, the voltages and currents obtained from digital computer simulations must be amplified before being applied to the relay under test. In addition they must first be converted from digital values to analog levels using a digital-to-analog converter. The hybrid nature of this approach permits CT and CVT models to be either analog (as with low-power analog simulation) or digital, as desired.

One problem with relay test facilities which use digital power system simulation is that the power system simulation does not occur in "real time", as it does with analog simulation. The power system simulation must be performed separately from, and ahead of, the relay test. Consequently, any response of the relay being tested is not automatically and immediately reflected in the power system simulation (i.e. there is no feedback from the relay to the power system during the relay test). For most test purposes, however, this is not a serious limitation (it is, after all, no different than the use of pre-recorded results from TNAs or model power systems).

Relay test facilities using digital power system simulation are in use by GEC (Williams and Warren, 1984), some university researchers (e.g. Coish et al., 1980), and at least one utility (Bornard et al., 1984).

D. LIMITATIONS OF RELAY TESTING TECHNIQUES

Relay testing facilities have serious practical limitations from the perspective of the power system utility. Principally, they are expensive to build, no matter which method is used for simulation of the power system. This is largely due to the need to drive the hardware with full rated voltages and currents. Driving powers are high—several kilowatts for current inputs, where the burden under fault conditions is orders of magnitude larger than the burden at rated input. Either the simulator itself must provide this power, or special high-quality amplifiers must be used. In either case, the cost of providing signal power is high.

When the cost of operating and maintaining a test facility is included, the expense of providing an in-house facility is greater than most utilities could justify. External facilities provide only a partial solution, since access is limited and inconvenient. While not serious problems for the occasional special study, these factors prohibit the use of external facilities for routine work.

Where hardware testing is the end objective, there is no reasonable substitute for conventional test facilities. Field testing is clearly more accurate, but it is so expensive, time-consuming, and disruptive to the electricity supply that it is impractical except for spot checks. Laboratory testing is therefore required.

As important as hardware testing, however, is protection scheme testing. Protection schemes for modern bulk transmission systems, in particular, are so complex that some sort of evaluation is required before a scheme is put into service, or significantly modified.

Relay test facilities have proven to be extremely useful for this type of evaluation. The relays are connected together in the laboratory to duplicate the eventual protection in the field.

This type of pre-installation testing, using a model power system, was used for extensive studies of the protection for B.C. Hydro's Peace River system (Hayden et al., 1971). More recently, the protection for B.C. Hydro's 500 kV submarine AC cable, between Cheekye on the mainland and Dunsmuir on Vancouver Island, was tested using a digital-computer-based test facility (Burk and Hindle, 1984).

As valuable as they have proven to be, however, relay test facilities are not well-suited for evaluating complete protection schemes. Firstly, test facilities typically drive only a few relays at a time. Yet utilities are understandably more concerned about the performance of the protection system as a whole, rather than just one or two principle relays. The influence of the scheme logic on security and dependability can be found only by studying the performance of the complete protection scheme.

A second limitation to the use of test facilities for protection scheme studies is the obvious need for the relay hardware to be physically available for testing. Thus, test facilities cannot be used where the hardware has not yet been constructed, or where it is not readily available for any other reason. This makes it difficult, if not impossible, to use these facilities for studies of conceptual protection schemes. Even the analysis of installed schemes is impossible unless a sufficient number of spares of the installed relays can be found to assemble a duplicate system for testing.

Utilities are thus in need of an alternative to relay test facilities for protection scheme studies.

CHAPTER III. DIGITAL SIMULATION OF PROTECTION SCHEMES

For evaluating protection schemes, digital simulation is an attractive alternative to relay test facilities. The simulated protection can be as extensive and complex as required. There is, for all practical purposes, no limit to the number of relays which can be included in the simulation.

Since there is no need for relay hardware, digital simulation is well suited for evaluating new relay designs and concepts, or for similar situations where hardware is not readily available. Setting and design changes are relatively fast and simple.

In-house digital simulation capability can be provided at a small fraction of the cost of relay test facilities. Suitable general-purpose computers are widely available, so little or no extra hardware would be required.

Capital costs are mainly associated with providing the necessary software. Maintenance costs are not a consideration. Operating costs consist mainly of the computer time used for the simulation, and the manpower required to set up and run studies.

With these advantages, the question arises: why have utilities not adopted digital simulation for protection studies? It has been widely used for research, mainly at universities, into the behaviour of general relay designs under specific conditions (Johns and Aggarwal, 1977; Rowbottom and Gillies, 1976; Humpage and Wong, 1978 and 1979; Peng et al., 1985; Klebanowski et al., 1980). It has also been used for evaluation of some new and suggested relay designs (Esztergalyos et al., 1978; Crossley and McLaren, 1983). It has not, however, been used to any significant degree by utilities studying the security and dependability of their protection systems.

There would seem to be two principal reasons why this is so. The first is the lack of software for protection simulation.†

In spite of the number of reported studies in which relays have been simulated, no proven relay models have been presented. Only in the case of Peng et al. (1985), and to a lesser extent Johns and Aggarwal (1977), were modelling details given. Typically, little or no detail is provided about the models used. Without detail it is impossible to judge the suitability of the models for industrial simulations, or to build on the experience gained.

The lack of relay models is not a long-term problem, however. Models can been developed. By comparing the behaviour of a relay model with that of the actual hardware, the model can be proven to be accurate.‡ The proving of relay models can be greatly aided by the use of relay test facilities, which permit such direct comparison between hardware response and simulated response. Once developed, the collection and cataloging of these models becomes a purely organizational issue. The models can be made widely available, spreading the investment in software development over many users.

Apart from the lack of relay models, a suitable protection simulation package is required into which the models can be incorporated. Only Humpage et al. (1974 and 1975) have reported a simulation package which appears to be sufficiently complete to be of industrial use. The program structure is now dated, however. Not enough detail has been provided to judge the practicality of

†Reliable software is already widely available, at modest or no cost, for power system simulation (e.g. Bonneville Power Administration's Electromagnetic Transients Program—EMTP).
‡Comparison with an actual relay is all that was missing in the Peng et al. work.

the methods employed, or the suitability of the techniques for simulation of comprehensive multi-relay protection schemes. Again, however, this is not a long-term problem: a suitable package can be developed.

The second, more serious reason why utilities do not use digital protection simulation is the large amount of computer time required. For individual simulations, the CPU time required† is comparable with the requirements for other, standard utility simulations (e.g. transient stability). Where only a few simulations are required the CPU load is thus acceptable. For protection security and dependability studies, however, thousands of individual simulations are typically required. It is the number of simulations which causes a problem.

Souillard, during the 1980 General Discussion of CIGRE Group 34, made the following statement on this point:

> *By its nature, a protection emits an on/off signal. For this reason it is very difficult to know whether an operation which gave a correct state is close to the change of state, or not, we do not have, as in an analog output device, a means of following up as a function of the variation of parameters to permit the application of interpolation or extrapolation principles, for envisaging the changes and limiting the number of tests. When the output device is of an "on/off" type, it is therefore appropriate to undertake very fine investigation, to detect all points missed in the examination.*

Even when many tests are conducted, the various relay outputs (and other binary signals) which are combined in the scheme logic must be examined individually. This is because the scheme logic tends to further obscure the

†For the simulations discussed in chapter VI, the CPU time required for simulation of both the power system and the protection was about 20 s on a VAX 780 computer.

existence of marginal operating conditions. Careful examination of the critical steps in the scheme logic is required to avoid overlooking potential misoperation.

This problem appears to be at the core of Muller's statement in a paper (Muller, 1980) presented to the same session of CIGRE:

> *The testing of protection systems is relatively expensive. Apart from the limitations arising from the testing device . . ., there is also a limitation on the complexity of the system being tested. This is determined predominantly by the number of signals which have to be evaluated. For the new systems which are to be developed, more internal signals result that is the case for combinations of tested elements. When there are too many internal signals the evaluations become too extensive. The computer* [by which he means the control computer of the testing facility he is describing] *is only of limited use under these circumstances because criteria can arise which are difficult to predict and therefore to programme.*

None of the published material on relay testing or simulation proposes a solution to these problems. Reducing the number of tests sacrifices the reliability of the conclusions. Yet unless the number of tests is greatly reduced, digital simulation is impractical for security and dependability studies of complex, multi-relay protection schemes.

Numerical logic replacement, a concept described next, offers a solution. It provides the "analog output" Souillard speaks of. Analog output levels from each relay are carried through the logical combinations which form the scheme logic, all the while preserving the necessary analog form. A reliable indication of marginal operating conditions is thus propagated far "downstream" in the logic flow from the source of the original problem—right to the circuit-breaker trip signals.

As a consequence, the number of signals which must be examined—the problem Muller spoke of—is greatly reduced. The number of simulations required—the problem Souillard spoke of—is also greatly reduced. And digital simulation becomes practical, even for complex multi-relay protection schemes, as will be seen in chapter VI.

A. NUMERICAL LOGIC REPLACEMENT

When relay output contacts are represented directly as Boolean ("on"/"off") quantities, it is not clear from the output how close the relay comes to operating. No warning is given of near-operation, or more importantly, near-misoperation.

In an effort to avoid overlooking potential misoperation in security and dependability studies, typical practice is to adjust simulation parameters in small steps. This requires a large number of simulations to cover the required range of operating conditions.

Numerical Logic Replacement, or NLR, greatly reduces the need for these small steps. With NLR, the state of the relay output contact is represented as a continuous (as opposed to Boolean) quantity. This continuous quantity, called a **pseudo-output**, takes on positive values when the contact is closed ("on") and negative values when the contact is open ("off"). The magnitude provides a measure of the margin by which the contact is open (or closed)—indicating how close the relay is, at any instant, to operation. (A small negative value of the pseudo-output, for example, indicates that the contact is open, but not far from closing.) The potential for misoperation can thus be seen directly from the value of the pseudo-output.

The idea of using an equivalent analog output for a relay, rather than the actual output contact, is not new. It is relatively common, when simulating individual relays, to display an internal (analog) signal as the "output". A signal is chosen which can be directly related to the state of the output contact. In Johns and Aggarwal (1977), for example, the output of the phase-comparator integrator was used. This "analog-output" technique was also used during model power system tests of relays for the B.C. Hydro Peace River protection (Engelhardt, 1985).

A problem arises, however, when the relays are combined into complete protection schemes. Protection scheme logic is implemented using Boolean operations (AND, OR, NOT) to combine the contact outputs of the individual relays. "Analog" levels cannot be used as input for these operations; neither can they be produced as output. The "analog-output" technique must therefore be abandoned to carry out the scheme logic. Protection engineers are thus forced to manually interpret the operation of the scheme logic to decide if misoperation of a particular relay could cause misoperation of the overall protection scheme. This tedious interpretation is excessively subject to human error.

The need for interpretation would be greatly reduced if the Boolean operations could be replaced by equivalent "numerical" operations. The equivalent operations would have to use relay pseudo-outputs as input. They would have to produce output of the same (analog) form as the input, so that the output could be used as input to subsequent operations. Finally, the relationship between the input and output for each equivalent operation would have to be directly analogous to the input-output relationship for the Boolean operation being replaced.

Such equivalent "numerical" operations exist, and form the basis for NLR. NLR outputs are directly analogous to the outputs of the corresponding Boolean logic elements, just as relay pseudo-outputs are directly analogous to the contact outputs. NLR outputs preserve the measure of operating margin conveyed by the relay pseudo-outputs, and can therefore be treated just like pseudo-outputs for use in subsequent operations. Consequently, it is possible to replace any sequence of logical operations with an equivalent set of NLR operations.†

By preserving a one-to-one correspondence between the actual Boolean operations and the replacement operations, the replacement process is made completely transparent to the person running the simulation. There is thus no additional risk of human error due to the replacement process.

1. Replacement operations

For relay "analog" outputs to be used in replacement operations, they must be offset (and inverted, if necessary) so that the level will be positive when the associated contacts are closed, and negative otherwise. It is the offset (and possibly inverted) value which becomes the pseudo-output.

Consider the logical AND combination of the output contacts of two relays i and j, with pseudo-outputs f_i and f_j, respectively. Relay i contact is closed if $f_i > 0$, and similarly for relay j. In terms of pseudo-outputs, the logical state TRUE is represented by $f_i > 0$, and the logical state FALSE is represented by $f_i < 0$. (Note that $f_i = 0$ is neither true nor false, since the logical negation NOT, described following, would not otherwise be equivalent to algebraic negation.) The AND combination of the output contacts is thus

†The timer model in appendix B uses an SR flipflop model implemented using NLR.

represented as

$$\text{AND}(f_i > 0,\ f_j > 0)$$

which is true if and only if

$$\text{MINIMUM}(f_i,\ f_j) > 0.$$

Thus the result of a numerical MINIMUM operation on the pseudo-outputs implies the result of a Boolean AND operation on the output contacts. As importantly, the magnitude of the MINIMUM result indicates the margin by which the result is true or false.

Similarly, a logical OR combination of two relay contacts

$$\text{OR}(f_i > 0,\ f_j > 0)$$

is true if and only if

$$\text{MAXIMUM}(f_i,\ f_j) > 0.$$

Thus the result of a numerical MAXIMUM operation on the pseudo-outputs implies the result of a Boolean OR operation on the output contacts. Again, the magnitude of the MAXIMUM result indicates the margin by which the result is true or false.

Finally, the logical negation

$$\text{NOT}(f_i > 0)$$

is true if and only if

$$-(f_i) > 0.$$

The result of a numerical negation on a pseudo-output thus implies the result of a Boolean NOT operation on the output contact. As for the AND and OR operations, the magnitude of the negation result indicates the margin by which the result is true or false.

Conversion of NLR results to Boolean results (where desired for display, for example) can be achieved using a simple function which produces a constant high-level output when the input is positive, and a constant low-level output otherwise.

The operation of NLR can be better understood by studying fig. 1, which shows the waveforms corresponding to an NLR EXCLUSIVE-OR operation

$$XOR = \bar{A} \cdot B + \bar{B} \cdot A.$$

The two upper traces show the input signals A and B, both of which are 60 Hz cosines, with B lagging A by 90°. The third trace from the top shows $\bar{A}$, which with NLR becomes $-A$. The fourth and fifth traces from the top are the $\bar{A} \cdot B$ and $\bar{B} \cdot A$ terms, respectively. With NLR, the logical AND operation $\bar{A} \cdot B$ is performed as an instant-by-instant minimum of $\bar{A}$ and B, as can be seen by studying the traces for $\bar{A}$, B, and $\bar{A} \cdot B$. The bottom trace shows the EXCLUSIVE-OR result, which is obtained as an OR result of $\bar{A} \cdot B$ and $\bar{B} \cdot A$. With NLR, the logical OR operation is performed as an instant-by-instant maximum of $\bar{A} \cdot B$ and $\bar{B} \cdot A$, as can be seen by studying the lower three traces of fig. 1. Positive values of the XOR output represent a TRUE condition (high state), while negative values represent a FALSE condition (low

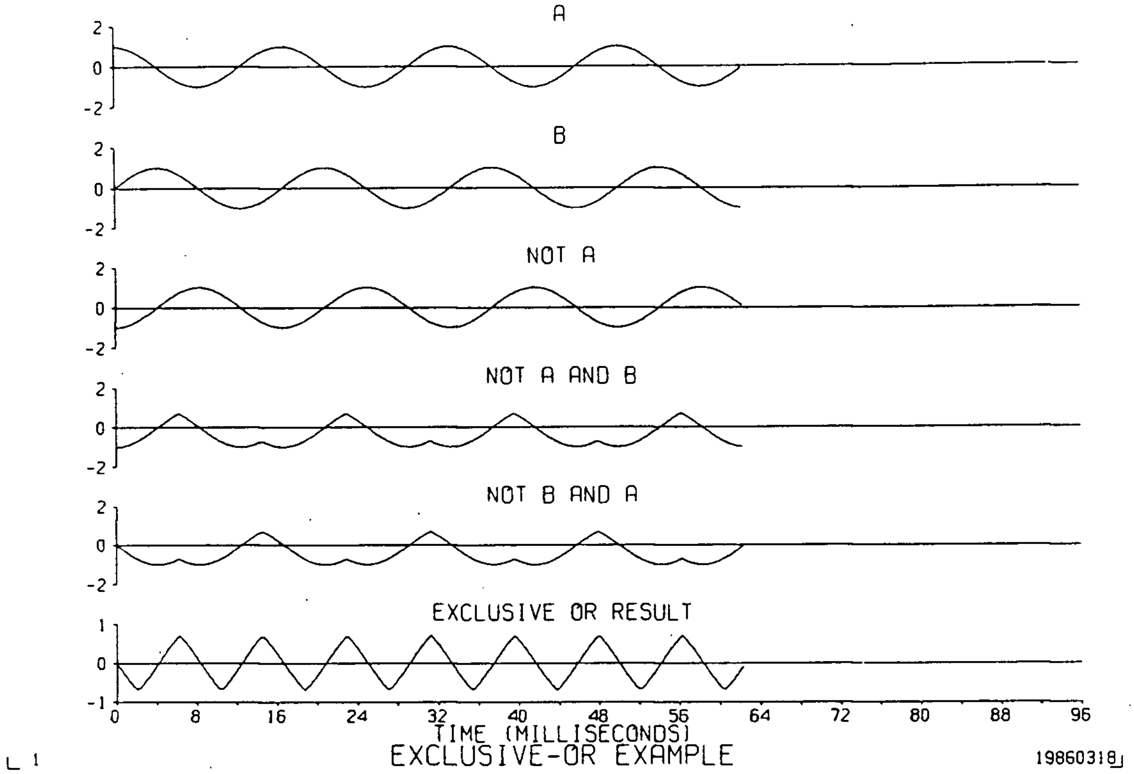


Fig. 1. Intermediate waveforms for NLR Exclusive-OR operation

state).

The XOR in this example serves as a polarity non-coincidence detector. Had an EXCLUSIVE-NOR (XNOR) operation been simulated (just the logical negation of the EXCLUSIVE-OR, and the algebraic negation of the NLR EXCLUSIVE-OR), it would serve as a polarity coincidence detector, which is a component of both the static phase comparator (Jackson, 1981) and the ASEA RALDA directional wave detector (Chamia and Liberman, 1978). In fact, the expression for the RALDA ***trip*** output given in the closure to Chamia and Liberman can be seen to be that of a two-input NLR EXCLUSIVE-OR, and the expression for the ***block*** output is that of an NLR EXCLUSIVE-NOR.

With a simple shift in the values representing TRUE and FALSE, NLR operations become identical to the logical operations used with Fuzzy Sets (see Zadeh, 1965). This is not surprising, since NLR can be viewed as an application of "multiple-valued" logic. This is not to say, however, that we are making use of Fuzzy Sets with NLR. Fuzzy Sets deal with elements which can simultaneously belong to more than one set, due to the "fuzziness" in the definition of the sets themselves. There is no such fuzziness here. A relay either operates or does not operate for a given simulation.

The object of using NLR and pseudo-outputs is to gain an indication of the sensitivity of the protection output to changes in relay inputs. For example, if the margin to contact closure is large, a relay is less likely to change state for a given change in input than if the margin is small. More particularly, by observing the magnitude and direction of the change in margin which accompanies a given change in simulation parameters, tests which will not produce a significantly smaller margin (i.e. risk of protection misoperation) can be avoided.

NLR provides the sensitivities which are needed to reduce simulation effort.

2. Selection of the pseudo-output

The selection of the appropriate pseudo-output for a relay is usually more obvious than it may first appear. For all relays, the state of the output contact is the result of a comparison between some value derived from current and/or voltage measurements, and a threshold value, often derived (perhaps indirectly) from one of the relay settings. In some cases, several such comparisons may be combined through logic to produce a trip output (e.g. directional comparison schemes).

For electromechanical relays of the induction disc/cup type, for example, the angular position of the disc/cup is "compared" with the position of the "a" contact. For static relays, the output of a timer or integrator is applied to a comparator circuit, where it is compared against a threshold (see fig. 2). Digital relaying algorithms generally use an explicit logical comparison between some computed value (impedance estimate, event counter, etc.) and a setting.

A timing element, such as would be used for zone 2 delay in distance schemes for example, is treated like an ordinary relay. In this case the measurement is the elapsed time since timer start, and the threshold value is the pickup or dropout delay.

In all cases, the pseudo-output is formed by taking the difference between the value derived from the measurements and the threshold value. Hysteresis, where it is used, is automatically accounted for by this procedure, and appears in the output waveform as an instantaneous shift in level as the response passes through zero.

Where relay operation requires some combination of events to be true, the detectors for the individual events are treated as individual relay elements, each with an appropriate output. The output for the relay as a whole is then the appropriate logical combination, using NLR operations, of the individual elements.

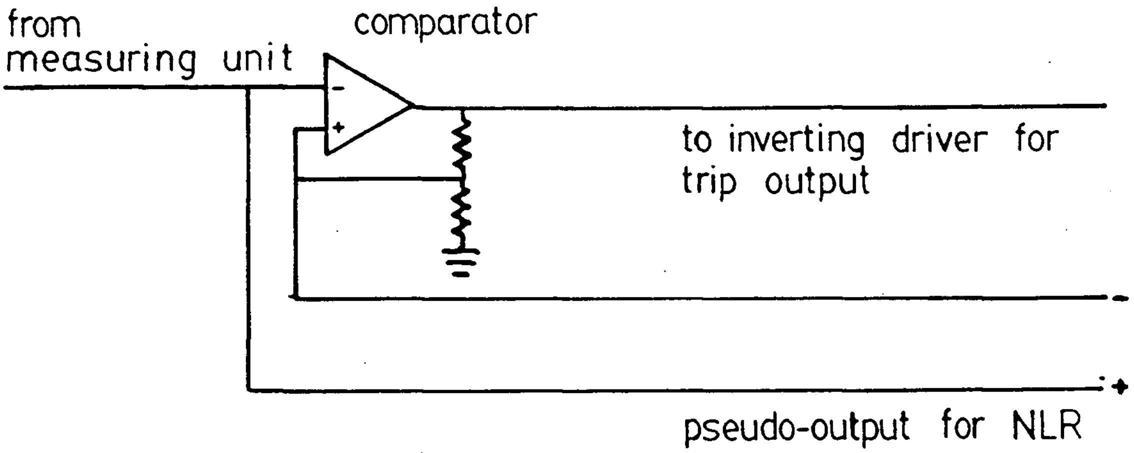


Fig. 2. Obtaining NLR pseudo-output for static relay

CHAPTER IV. MODELLING FOR PROTECTION SIMULATION

A. POWER SYSTEM MODELLING

Usual practice for power system simulations is to use detailed modelling only in the immediate study area. Increasingly approximate representations are used as the (electrical) distance from the study area increases. Modelling in the areas of the fault and the relays should be as detailed as practical, particularly at the voltage level where the fault occurs. (The effects of approximations in the modelling of adjacent higher and lower voltage systems tend to be "swamped", to some extent, by the impedances of the interconnecting transformers.) Modelling approximations at a few busbars distance from the fault and relay locations will have a greatly-reduced effect on relay voltages and currents due to the "swamping" effect of the intervening system.

For protection studies, the voltage sources and the network must be set up so that the steady-state solution more or less matches results from other types of programs. Without the fault applied, the steady-state solution must produce line flows which are reasonably close to those obtained from a power flow program, for the same loading condition. With the fault applied, the steady-state solution must produce approximately the same short-circuit currents as are obtained from a short-circuit program. This matching of pre-fault and post-fault solutions with results from power-flow and short-circuit programs is required at all relay locations and all fault locations being considered.

When portions of the transmission system are replaced with network equivalent circuits, satisfactory matching may be possible only with more complicated equivalents than those usually used for switching-surge studies. In the latter case the line is assumed to be open at one end; a single-bus Thevenin equivalent circuit for the feeding network is then sufficient to obtain the correct short-circuit currents, and there is no pre-fault power flow to match.

For protection studies, however, an equivalenced portion of the network will generally be connected to the retained network at more than one location. The assumption of a radial connection, implicit in the development of single-bus Thevenin equivalent circuits, is thus no longer valid. If the effects of coupling between the various connection points are ignored, it may be impossible to obtain the correct pre- and post-fault power flows. To preserve the coupling, it is necessary to use multi-bus Thevenin equivalents.

These equivalents can be large, and are tedious to compute. For a two-bus equivalent,† for example, which would be used where there are two connections from the modelled higher-voltage system to a particular lower-voltage network, twenty-one matrix elements are required (allowing for symmetry) as compared with six for the usual single-bus equivalent. Where four or five connections exist between the modelled voltage level and an underlying lower voltage system, the work involved in computing an equivalent can be considerable.

Multi-bus Thevenin equivalents will likely be required only for equivalents close to the study area. At a few busbars distance from the study area single-bus equivalents are likely to cause insignificant errors in the transient response, and only small errors in the steady-state fault levels.

Whether equivalents are single- or multi-bus, they must represent not only the proper power-frequency impedance, but the higher-frequency impedances as well. To develop such equivalent circuits with reasonably good frequency

†Appendix A describes the derivation of a two-bus Thevenin equivalent used for the simulations described in chapter VI.

response is still more of an art than a science. An interesting technique has been described by Morched and Brandwajn (1983).

In switching-surge studies, the single-bus Thevenin equivalent circuit is often modelled as an inductance, which produces the correct power-frequency short-circuit current, in parallel with a resistance $R = Z_{surge}/n$. This resistance approximates the impedance seen by travelling waves from the switched bus entering the n transmission lines, each of surge impedance Z_{surge}, connected to the bus.

For protection studies, however, the frequencies of interest are too low for this approximation to hold. Simple single-frequency equivalents must therefore be used at some distance (electrically) from the study area. Typically this will require modelling of the majority of the high voltage system, and at least the local underlying lower-voltage system.†

Unfortunately, common practice for protection simulations is to model only that portion of the system which is directly under study (e.g. Johns and Aggarwal, 1976 and 1977; Breingan et al., 1979; Redfern et al., 1980; Girgis and Brown, 1981 and 1983), using a simple single-frequency Thevenin equivalent source connected directly to the study network. This abrupt truncation of the transmission system leads to reflection transients in the modelled system which are unrelated to those of the actual power system.‡ The reflection transients which arise within these overly-simplified systems tend to be predominantly of single (and relatively high) frequency. Reflection transients which arise in more realistic transmission networks do not necessarily show any single dominant

†This is consistent with the experience of the author, B.C. Hydro, and CESI (Lionetto et al., 1980).
‡An example of the effects of truncation on system waveforms and protection response can be found in chapter VI.

frequency, and contain components of relatively low frequencies, sometimes below that of a second harmonic.

The classic paper by Swift (1979), while informative on the matter of reflection transients, does not fully discuss the effects of transmission-line terminations on the frequency and waveshape. The frequency of the transients is determined not solely by the reflections at the end of the line, as Swift's paper implies, but also by reflections occurring deeper within the connected system. Thorp et al. (1979) have published results of studies with a laboratory model of the American Electric Power system which show considerable variation in the frequency of the dominant resonance with the extent of the connected network.

The degree to which the connected network influences the resonance frequency depends on the impedance mismatch which the termination presents to the line. A clear limiting case is the perfect match produced when a transmission line is connected to (i.e. terminated by) an identical line, with nothing connected to the intervening bus. The extent of the "connected network" (the length of the second line) would obviously be as much a determining factor in the resonance frequency as the study line. In this case there is no energy reflected at the interface, so the resonance is entirely due to energy crossing the interface into the termination and reflecting back across the interface into the study line.

For the resonant frequency to be correct, an equivalent must present the study network with an essentially-correct impedance at all frequencies. Thus, except where the study line connects to a stiff bus (in which case it becomes essentially decoupled from the remainder of the system beyond that bus), the use of simple single-frequency equivalents in the immediate study area should be avoided.

Even geographically-small areas, such as Japan, can experience "large-system" reflection transients (Okamura et al., 1980; Kudo et al., 1985; comments of Suzuki during General Discussion of CIGRE Group 34, 1978) due to mixed overhead-line/cable systems, since lower cable propagation velocities reduce the resonance frequency. Thus even when dealing with geographically-small areas, the extent of the system to be modelled must be considered carefully.

1. Transmission Line Modelling

The simple RL line model used for classical steady-state protection calculations is entirely inadequate for transient simulations. A better representation is a cascade connection of short nominal-pi sections, with mutual coupling represented between phases and between parallel lines on the same right-of-way. A double-circuit line would thus be modelled as cascaded six-phase pi-circuits. The length of each section is determined by the highest frequency of interest in the transient simulation. Distributed-parameter models are preferable to pi-circuits because they give the proper response over the entire frequency range. Ideally, frequency-dependent effects should be modelled for at least the ground-return mode.

To model the complete line with sections of untransposed lines is straightforward with nominal pi-circuits; reliable distributed parameter models for untransposed lines are still in the development stage.

2. Load Modelling

Load modelling for transient simulation is still at an early stage. The minimum acceptable load representation is a three-phase power-frequency Thevenin equivalent, which at least ensures that steady-state fault and pre-fault flows will be correct.

For loads close to the relay location, and which experience depressed voltage during the faults under study, some attempt at modelling the voltage behaviour of the load may be justified for medium term (e.g. reclosing) simulations. For short term simulations (e.g. fault application), it may only be necessary to model the frequency behaviour of the load.

Ontario Hydro have made measurements of the frequency behaviour of representative distribution feeders by applying signal-processing techniques to transient responses recorded during staged system disturbances (Morched, 1985). The results were used to synthesize models for the feeders. These models were of the form of a parallel connection of R and L, connected to the system through a cascade connection of pi-sections (in one case using non-zero shunt conductance to represent tapped loads). In the cases studied, excellent matches were achieved between the measured frequency behaviour and that of the synthesized models.

3. Transformer Modelling

Power transformers in protection studies can usually be adequately represented as coupled windings with constant resistances and constant self and mutual inductances. The resistances and inductances can be derived from the power-frequency interwinding impedances, as for steady-state calculations. Where the operation of transformer protection is under study, and it is important to account for inrush currents or harmonics from saturation effects, a more elaborate representation can be used, at least accounting for the non-linearity of the magnetization curve.

Brandwajn et al. (1982) have shown how a coupled multi-winding transformer model can be produced from readily-available data. Nakra and Barton (1974) presented results for a coupled multi-winding transformer model which included saturation and hysteresis effects.

4. Generator Modelling

Generators can usually be modelled adequately as equivalent voltage sources E" behind subtransient inductances L_d'' (analogous to the representation used with short-circuit programs) for the short time spans involved in fault-clearing studies. This is particularly true where the relay location is separated from the generation by the generator transformers, or the transformers plus some transmission, so that the generator impedance is somewhat masked by the intervening impedance.

For studies of longer duration, where the dynamics of the generator and exciter must be accounted for, or for studies of the generator or generator transformer protection, more exact generator modelling will be required. Detailed generator models have been developed for sub-synchronous resonance studies using the Bonneville Power Administration EMTP, which also has the capability to represent exciter and governor dynamics (Brandwajn and Dommel, 1979).

Transient programs with detailed generator and exciter models provide a particularly accurate way of determining the effect of generator swings on the protection. Although some transient stability programs have rudimentary protection modelling capability, the absence of any zero-sequence representation limits their use to phase faults. Transient programs such as the EMTP allow all types of faults to be considered.

For long duration studies, it should not be necessary to consider the effects of electromagnetic transients over the entire interval, so that large step sizes can be used. Aggarwal and Johns (1980) advocated continuing the transient simulation over the entire sequence from fault incidence through to auto-reclosure. This is unnecessary, since realistic reclosing times are of the order of tens of cycles for practical power systems (Ellis et al., 1966, for example, found a value of ≈ 0.5 seconds for the early B.C. Hydro Peace River system). By this time, electromagnetic transients will have decayed to insignificance, so that, from the transient point of view, reclosure is essentially from a new steady-state condition.

5. Fault Modelling

Fault impedance is commonly modelled using a linear resistance to represent tower footing resistance (for ground faults), and a non-linear resistance (similar to, for example, a zener diode characteristic, except bipolar) to represent arc impedance (Hayden et al., 1971; Marsman, 1980). It may be acceptable to ignore the nonlinear characteristic for some studies. The IEEE Power System Relaying Committee (1985), for example, have suggested that "the nonlinear nature of the arc generally merits consideration only for the lower voltages or for time delay backup relaying at any voltage". Where ground wires are not used, tower footing resistance will likely dominate any arc "resistance" for ground faults; a linear resistance will thus suffice in these cases.

Where the arc voltage is to be represented, an empirical expression developed by Warrington (1931) can be used to estimate the arc voltage for a given fault current level:

$$V = 8750\ l\ /\ I^{0.4}$$

where l is the arc length in feet, in still air, I is the fault current level in amperes, and V is the arc voltage in volts. It is apparent from the data presented in the original paper that the voltage and current in this expression are RMS values. (Warrington does not explain how the RMS values were computed from the distorted waveforms.)

B. PROTECTION MODELLING

1. Transducer Modelling

The digital modelling of instrument transformers has been discussed in a number of published papers (e.g. Wright and Rhodes, 1974; Rowbottom and Gillies, 1976; Wong and Humpage, 1978). The main effects which must be accounted for by instrument transformer models are:

- core saturation effects, including remanence and hysteresis for best modelling of current transformers (CTs). The effect of the magnetic core non-linearities may generally be ignored for capacitive voltage transformers (CVTs), except where ferroresonant possibilities are of concern.

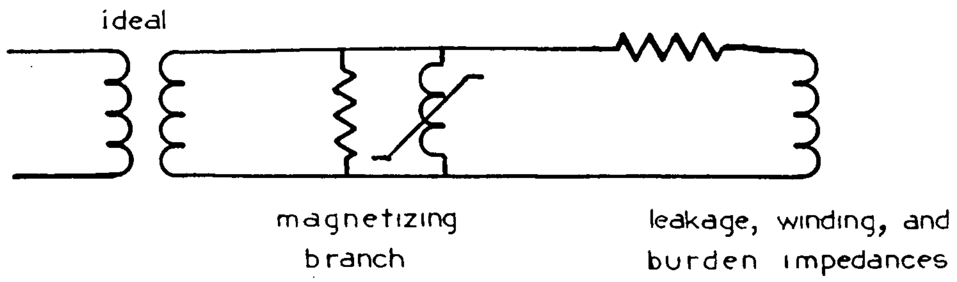
- relaxation transients, which occur with both CTs and CVTs when the primary energization collapses to zero, due to the decay of charge and flux from the energy-storage mechanisms intrinsic to these devices. Related to relaxation transients are the energization transients which occur when de-energized instrument transformers are suddenly re-energized, such as occurs after a line is reclosed. Relaxation transients in CTs can cause slow dropout of overcurrent relays, while CVT relaxation transients can cause incorrect operation of distance relays for close-up faults.

- bandwidth effects, particularly CVT resonances due to the interaction of the capacitive voltage divider with the compensating inductance. Douglass (1981) has published the results of measurements on CTs, which show the frequency response to be essentially flat to beyond 20 kHz when the CTs are properly applied. Bandwidth is thus not an issue for CTs (per se—see next point). For CVTs the situation is more complex due to the tuning inductance used for reducing power-frequency phase error. Chamia (1980) gives the useful frequency range for a CVT as being from 20 to a "few hundred" Hertz. CIGRE Working Group 36-05 have published (1984) a plot of relative transformation ratio versus frequency for a 220 kV CVT for 50 Hz systems, which shows a narrow peak of 2.7 (relative to 1.0 at 50 Hz) at about 170 Hz, and another broad peak of over 3.1 at about 800 Hz.

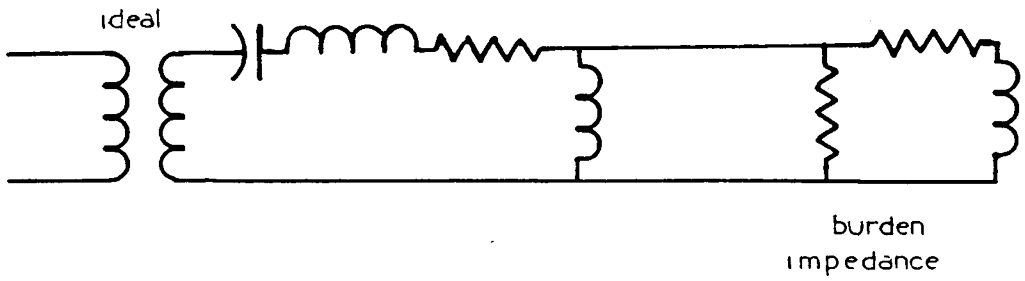
- burden effects, particularly under transient conditions. Apart from the well-known effects which the burden can have on its transducer under steady-state power-frequency operating conditions, the transient response of the transducer will clearly be affected by the transient behaviour of the burden. Since the exact burden composition is almost never known (particularly for CVTs, which supply a collection of relays, etc.), some assumption must be made. The usual assumption of a Thevenin equivalent (power-frequency) impedance at least ensures that power-frequency modelling is correct. The value of detailed CT and CVT models is debatable, however, when the burdens are represented so imperfectly. Sensitivity studies are required in this area, along with measurements of the transient characteristics of typical installed CT and CVT burdens (total burden, that is, including wiring and composite relay/metering burdens). It is essential that burden representations be developed which can be used with greater confidence than can the present power-frequency "equivalent" burdens.

Figure 3 shows equivalent circuits which can be used for CT and CVT modelling. Neither is very sophisticated, but data for both can be either derived or estimated from available information, and at least the most important transducer effects are represented.

The CT magnetizing branch uses a non-linear inductance as a core model to account for saturation effects. Wright and Rhodes (1974) have reported good results using the common "two-slope" model. Rowbottom and Gillies (1976) used a more complex model which accounts for saturation, hysteresis, and remanence. This latter model appears to be a good compromise between accuracy of representation and practicality of implementation.



(a) CT model



(b) CVT model

Fig. 3. CT and CVT equivalent circuits.

The linear resistance shown in the CT magnetizing branch is used to produce eddy-current-like loss effects. This is a commonly-used artifice.

The CT burden is a composite of the usual series RL power-frequency equivalents of the burden impedance, secondary winding resistance, and leakage inductance.

The CVT model includes a series RLC branch representing the equivalent input capacitance of the capacitive voltage divider, the phase-shift compensating inductance, and the damping resistance. This determines the major frequency response of the CVT, and the high-frequency capacitive relaxation transients. The shunt linear inductance provides an approximation to the magnetizing inductance of the internal magnetic VT, and permits representation of the low-frequency inductive relaxation transients.

The burden has the format required for the ANSI transient tests for CVTs, and is intended to permit "tuning" of the damping resistance to obtain reasonable transient characteristics. The series RL limb would ordinarily be used in the simulations, being set to the power-frequency equivalent burden impedance.

2. Relay Modelling

Protective relays may be modelled in varying degrees of detail. Where digital models of relays have been used for published work, they appear to be mostly "generic" (e.g. Johns and Aggarwal, 1978). Generic models share the same general principles of operation as the actual relays (e.g. mho relays based on block-average phase comparison), but omit details such as input filtering or input sensitivity levels. Generic modelling can be quite useful for studying basic protection concepts, and can be used for modelling the less-important relays in a protection scheme (e.g. some supervisory relays, relays used for local backup protection, etc.)

The principal measuring relays in a high-speed protection scheme are likely to require more detailed modelling. This could include the specifics of the input circuitry (including filters), comparator details (such as input sensitivity levels), and specifics of the relay output circuitry (such as the blocking and latching features used in the Westinghouse SD-2H relay described in appendix B). This more-detailed modelling naturally requires specific knowledge about the relays in question.

The most advanced level of detail requires not only extensive information about the relay circuitry, but also an actual relay and access to a sophisticated facility for testing it. The testing is needed to verify the digital model by subjecting both the actual relay and the model to identical input waveforms and comparing the output (and selected internal) signals for the two.

Of the two basic problems associated with relay modelling—collecting the necessary detailed data about the relay, and preparing the actual digital model—collecting and interpreting the data may be the most difficult task. Manufacturers' descriptive bulletins and instruction manuals do not necessarily contain all required details.

For example, although the manufacturer's instruction booklet was very helpful when modelling the SD-2H relay described in appendix B, the "Q" or "quality factor" of the memory and input filter were not given. An alternate method had to be used to find acceptable values.

Because of the difficulty of obtaining data, specific models should be used only where absolutely necessary (e.g. principal measuring relays); generic modelling is appropriate for the remaining relays.

Once the necessary information has been collected, the actual modelling is generally straightforward. The relay input circuits, which transform the measured currents and voltages into the quantities needed by the comparator, are generally linear and can be modelled using state equations. Although various techniques are available for solving state equations numerically, the excellent numerical stability of central difference equations (which form the basis for implicit trapezoidal integration) make this the technique of choice for power system transient applications (Dommel, 1969). While other techniques theoretically offer better accuracy, experience has shown that these techniques are mostly unsuitable, being numerically unstable unless used with impractically-small step sizes.

The comparators themselves are generally non-linear, and are of varying difficulties to model. Polarity-coincident (static) two-input phase comparators, for example, require only straightforward EXCLUSIVE-NOR logic. Some two-input amplitude comparators, by way of contrast, require modelling of a multi-rectifier bridge circuit with an RC load circuit, which is a much more difficult modelling task. No single approach can be recommended.

Initialization of the comparator, particularly where integration of some kind is used at the output stage, can be a more complex task than the development of the iterative equations. This task is simplified by making use of the maximum and minimum limits on the output range. It is usually possible to identify the input conditions which cause the output to leave one limit and move into the "active region" toward the other. (The output will reach one of the two limits at least once per power-frequency cycle if the initial condition is from the steady state, since the relay cannot drift in the "undecided" intermediate region indefinitely.) The examples in appendix B clarify the procedure.

In extreme cases, the initialization can be performed by a "silent simulation", wherein a "pre-simulation" of one or two (power frequency) cycles duration is performed using the same equations as the main simulation. The pre-simulation is started from some assumed initial condition. Only the final value reached in the pre-simulation is retained (hence the term "silent"), this being the initial condition for the main simulation.

The error in the pre-simulation due to the assumed initial condition will be corrected when the comparator reaches the appropriate output limit.† The comparator output will then be reset to the correct value, and will leave the limit again at the correct time. The remainder of the pre-simulation will then be correct. Provided that the appropriate output limit is reached at least once during the pre-simulation, the initial condition for the main simulation will be correct.

Although silent-simulation is a brute force technique, it may be the most practical method of initializing highly non-linear comparators.

Another important aspect of relay modelling is establishing the integrator gain for relays with integrating (averaging) comparators. For a fixed output trip threshold, the speed of integrator-type relays is directly proportional to the integrator gain. The maximum value of integrator gain (which determines the theoretical maximum operating speed for the relay) is determined by the measurement uncertainty inherent in the comparator.

Measurement uncertainty shows up as a ripple in the comparator output—the rectifier ripple for an amplitude comparator, for example. The maximum gain must be low enough to ensure that the relay does not operate on this ripple for steady-state inputs just below setting. Since the gain may have to be reduced below this value to ensure security under transient conditions, a

†If the steady-state inputs are such that the comparator would be high, the appropriate limit would be the high limit. Otherwise, the appropriate limit would be the low limit.

convenient model parameter is the fraction of the maximum gain which is to be used.

A detailed example of the calculation of the maximum integrator gain is given in appendix B for the single-input amplitude comparator used in the over-current relay model.

3. Protection Scheme Modelling

a. Accounting for pilot channel delay time

Since most protection applications use communication between relays at different locations (usually at the two ends of a transmission line), it will usually be necessary to account for the delay associated with the pilot channels.

During the later portion of the simulation, the signals at the receiving ends of the pilot channels will be identical to the signals at the sending ends, except delayed by the channel time. The delay can be easily handled in the simulation by "reaching back" in time (time-delaying the sending-end signals) by the amount of the delay.

At the start of the simulation, however, "reaching back" requires knowledge of the signals at the sending-end before the start of the simulation. Since the pilot channel signals are derived from the relay outputs, it is necessary to determine the output of the relays before the start of the simulation (during the steady-state operating period). The only way of finding the relay outputs is to perform a "pre-simulation", identical to the main simulation except that the results would be used only for computation, and not for display. The pre-simulation would have to cover one full delay period before the start of the main simulation.

The need for the "pre-simulation" can be avoided if the pilot channels can be assumed to be completely quiescent during the initial delay period. If the protection system is known to be in an inactive, steady-state condition prior to the start of simulation, the assumption of complete quiescence would be reasonable for permissive- and transfer-trip channels.

C. COMBINING SIMULATIONS FOR THE POWER AND PROTECTION SYSTEMS

Two possible approaches can be used for combining the power system simulation with the protection simulation. The first approach is analogous to that used with analog relay test facilities, where the power system and protection function together at every instant in time. In digital simulation, both systems would be solved simultaneously at each time step before advancing to the next. This is the **simultaneous** approach.

The second approach is analogous to the one generally used with test facilities which use digital power system simulation. In these facilities, the voltage and current waveforms are often recorded on magnetic tape and played back through amplifiers for testing the relays. In this **sequential** approach, the power system and protection function separately, one after the other.

The simultaneous approach has the advantage of directly accounting for the effects of protection operation on the power system (circuit breaker opening and closing). These effects cause some difficulty with the sequential approach, since circuit breaker operations must be predicted when setting up the power flow simulation. This is possible in simple cases (e.g. fault clearing on a parallel line) by running a preliminary simulation to determine when the operations take place (e.g. circuit-breaker set to open after 70 ms, with the time of 70 ms obtained from a preliminary simulation).

A related problem with the sequential approach is the need to prepare special models wherever feedback loops are encountered within the scheme logic. The reason the special models are needed is that feedback can only be accounted for when everything encompassed by the feedback loop is simulated together (simultaneously). With the sequential approach, only individual models (which could be of relays, timers, logic blocks, or selected portions of the scheme logic) are simulated simultaneously.

In practice, however, the need to produce special models is not a serious disadvantage, since feedback loops in the protection scheme logic generally occur only where pilot channels are used. The required models are thus of relatively standard form (e.g. permissive trip logic) in most cases.

In the author's view, the advantage of the simultaneous approach is outweighed by several practical disadvantages. Firstly, the simultaneous approach requires a very large and complex program for the joint simulation of the power system and protection. The relay models must be re-entrant, complicating the programming and increasing storage requirements. The large number of subroutine calls required (one for each use of the model, at each time step) reduces program efficiency. In general, programming, program additions, and program maintenance are considerably more complex than with the sequential approach, which uses more-or-less independent program segments.

Secondly, the simultaneous approach provides only a limited choice of solution techniques. The entire power system and protection simulation must be either digital or analog. Digital simulation may use only time-domain methods. Further, if the parts of the program dealing with power system simulation are intricately interwoven with the protection simulation portions, the power system simulation method will be "locked-in" to the final program.

The sequential approach is virtually free of limitations of this nature. Digital or analog simulation may be freely intermixed, as suits the circumstances; in a hybrid simulation facility, actual relays and digital models of relays can be used interchangeably. This is possible because the inputs for each model are pre-computed, so that rather than simulating the entire protection scheme in real-time, it is only necessary to be able to transfer data at real-time rates from memory to the necessary digital-to-analog converters, and from the necessary analog-to-digital converters to memory. This is quite a modest requirement, employing well-tested technology. The advantage of this capability is that accurate digital models can be developed and tested against the actual hardware under *identical* conditions. Since both model and hardware can have identical appearance to the remainder of the simulation package, either can be "dropped in" to the overall protection simulation with little effort.

Either Fourier-transform or time-domain solution methods can be used for digital models of either protection system components or the power system. Power system voltages and currents do not even have to be simulation results—recordings of actual power system voltages and currents can be used if available.

A further advantage offered by the sequential technique is that the various independent portions of the protection (phase and ground relaying, for example) can be simulated independently. This feature can offer considerable savings in computation when investigating the effects of changing the parameters of a relay (or set of relays) on protection performance, since all portions of the protection which are not dependent on the output of the relay under study can be simulated separately and stored.

For most security and dependability simulations, circuit breaker operations due to the protection are either irrelevant to the study or easily predetermined. The sequential approach is therefore usually the best choice for these studies.

CHAPTER V. MODELLING THE B.C. HYDRO PEACE RIVER SCHEME

A. *INTRODUCTION*

This chapter describes the modelling used for digital simulations of the B.C. Hydro Peace River system. The simulations were performed, using the techniques described in the previous chapter, to demonstrate the feasibility of digital protection simulation using NLR. The modelled protection is that used on the B.C. Hydro 500 kV transmission line designated 5L1, part of the Peace River transmission system. The protection is comprehensive enough to show that digital simulation using NLR is feasible for practical protection schemes. While the simulations are for a transmission protection scheme, the principles involved are sufficiently general not to limit the conclusions drawn from this research.

The simulations have been designed to demonstrate the operation of the 5L1 protection for critical benchmark faults. The simulation procedure is very similar to that which would be used in checking out a proposed protection scheme during the planning process. Some relay parameters have been determined experimentally.

B. *B.C. HYDRO PEACE RIVER SYSTEM*

The B.C. Hydro power system consists of some 10.5 GW (nameplate) of generation, of which 9.3 GW is hydroelectric. The majority of the generation is located at sites remote from the major load centre at Vancouver, in the southwest corner of the province. The bulk of the power generated at these remote hydroelectric sites is carried by 5088 circuit-km of 500 kV transmission (including 38.5 km of submarine cable), which spans the width of the province from Vancouver Island to the Rocky Mountains (there interconnecting with the Trans Alta Utilities system in Alberta), and some 60% of the length of the province from the U.S. border in the south (there interconnecting with Bonneville Power Administration (BPA) in the state of Washington), to the G.M. Shrum and Peace Canyon generating stations of the Peace River system, 800 km to the north.†

The Peace River portion of the B.C. Hydro power system was the first of the B.C. Hydro 500 kV system to be developed (Ellis et al., 1966), coming on-line in 1968. This installation featured the use of braking resistors, fast solid-state exciters, and series compensation, in order to ensure the stability of over 900 km of radial 500 kV system. Even now, some 600 km of this system, from Kelly Lake substation (southwest of 100 Mile House) north to G.M. Shrum and Peace Canyon generating stations (near Fort St. John), is essentially radial.

It is the northern-most portion of this system which is of immediate interest for this study, from the 2730 MW G.M. Shrum and 700 MW Peace Canyon generating stations south to the Williston substation near Prince George, at the end of 277 km of 500 kV transmission. Details of this area of immediate interest, as modelled, can be found on the one-line diagram of fig. 4. (A list of the three-letter station abbreviations can be found in appendix A.)

The protection under study is for transmission line 5L1, a 277 km 500 kV line of flat single-circuit construction, running from G.M. Shrum to Williston. Neighbouring 500 kV lines are 5L4, 14 km long (modelled as

†One-line diagrams of the majority of the 500 kV system, as modelled, along with details of the power system modelling, and complete listings of the EMTP input data used for this study, can be found in appendix A.

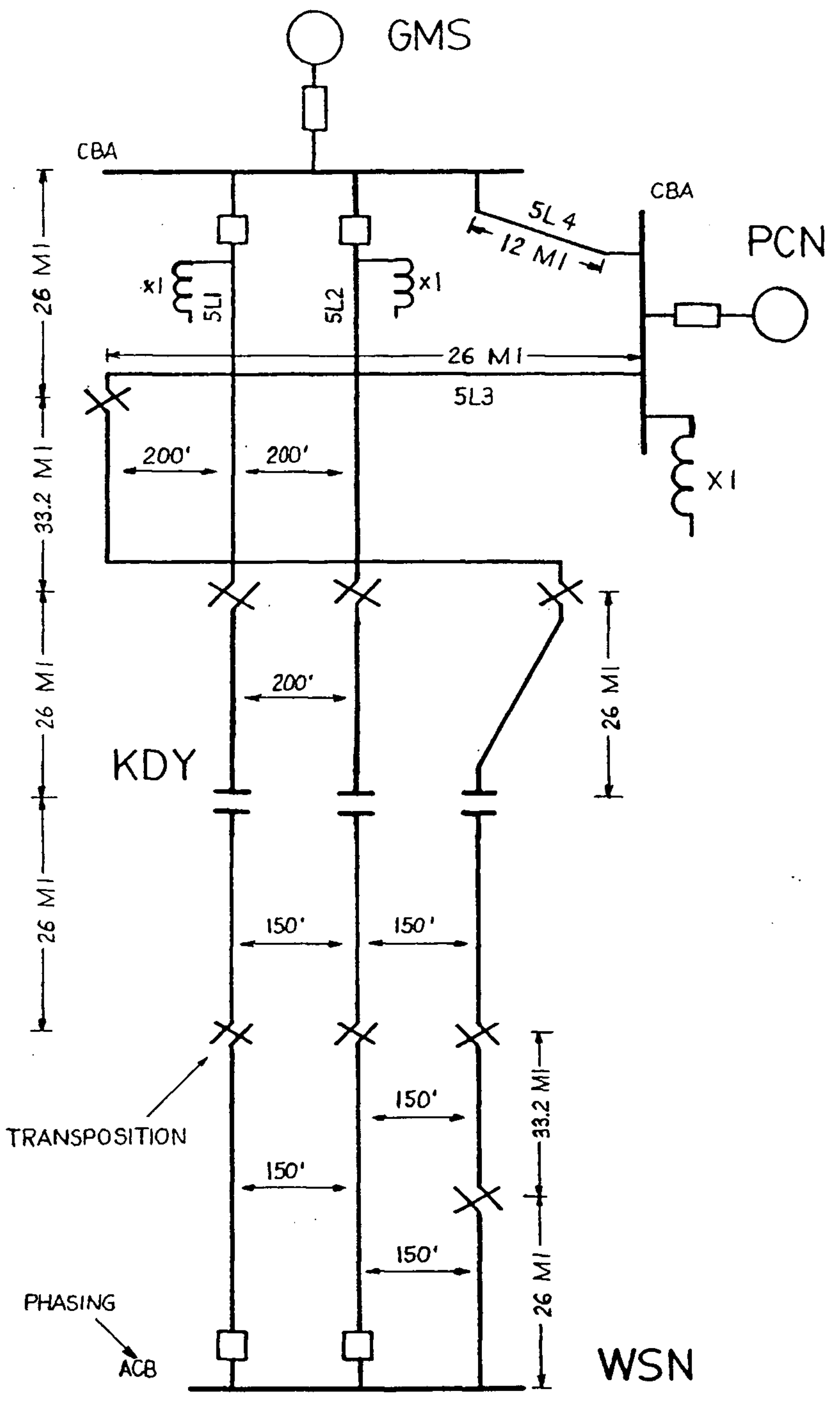


Fig. 4. Transmission detail for northern Peace River system

19 km—see appendix A) from G.M. Shrum to Peace Canyon; 5L2 and 5L3, the 277 km long lines running parallel to 5L1; and 5L11 and 5L12, the 329 km long parallel lines connecting Williston with Kelly Lake.

Series capacitor banks provide 50% compensation in the three lines between G.M. Shrum and Williston (at Kennedy station), and in the two lines between Williston and Kelly Lake (at McLeese station). The series capacitor banks are equipped with protective gaps which bypass dangerously high currents (Batho et al., 1977; Mansour et al., 1983). These gaps have been modelled only at Kennedy (for 5L1, 5L2, and 5L3; see appendix A); all other series capacitor installations have only the effective series capacitance modelled (i.e. gap flashing is inactive).

Shunt reactors are used throughout the B.C. Hydro 500 kV system. For the Peace River transmission, these consist of standard-rated ($X=2040\Omega$) single-phase units, connected in a grounded-wye configuration. Integral numbers of these standard banks can be connected to the transmission lines (rather than the bus), as required. For the study at hand, one of these standard banks is in service at the north ends of each of 5L1, 5L2, and 5L3. (Reactors have been modelled on the associated bus for all lines except 5L1 and 5L2, for which the exact location is significant for this study.)

The power system model used in this study does not include the G.M. Shrum braking resistance (used to enhance stability during loss of one of the 500 kV lines to Williston). Nor has any detail of the generators (exciters, governors, etc.) been included for this study. Generation is modelled as E'' behind L_d'', as for conventional (steady-state) fault studies.

1. Portions of the System not Represented

For buses remote from the immediate study area, lower voltage portions of the system are represented by single-bus (three-phase) Thevenin equivalents at 60 Hz, so that steady-state fault and pre-fault flows will be correct. There is an error associated with this approach where the lower voltage system is not radial from the high voltage bus, which is the case here for many of the buses south of Kelly Lake (the 230 kV system underlies the 500 kV system in this area).

Comparisons between transient model steady-state fault results and results from a conventional (steady-state) fault study program showed the error produced by single-bus Thevenin equivalents south of Kelly Lake to be acceptably small for faults within the study area. Between Williston and Kelly Lake, however, the 500 kV system is essentially in parallel with a portion of the 230 kV system. To reduce steady-state errors for faults near Williston, a two-bus Thevenin equivalent was required at Williston and Kelly Lake when equivalencing this underlying 230 kV system.

C. B.C. HYDRO 5L1 PROTECTION

A detailed description of the Peace River protection is given in Hayden et al. (1971); only a general description is given here. Details of the relay models and a listing of the Transient Response Processor (TRP) commands used to simulate the protection can be found in appendix B. The scheme consists of nearly identical primary and secondary protection. Only the primary protection and the unique aspects of the secondary protection will be discussed here.

The protection is basically arranged as two independent configurations (underreaching direct transfer trip and over- and underreaching permissive trip with reverse blocking) for both ground and phase faults. The reverse blocking, which is equipped with a 100 ms memory (dropout delay), is essential to ensure security for faults clearing on parallel lines. Without reverse blocking, the sequential clearing of the two ends of a faulted parallel line could cause the permissive trip scheme to mistakenly indicate an internal fault. The reverse blocking feature will be demonstrated in chapter VI.

1. Phase-fault Protection

The phase-fault protection, for which the AB phase-pair elements are shown in logic-diagram form in fig. 5, is built up from three Westinghouse Canada type SD-2H memory-polarized mho relays. The underreaching elements, designated **21L1**, are set to reach 77% of the compensated line "length" (35.4Ω at 85°), with a "lens" impedance characteristic obtained by requiring phase coincidence within ±82.5° rather than the usual ±90°.

The overreaching elements, designated **21L2**, are set to reach 134% of the uncompensated line length (123Ω at 85°), with a lens impedance characteristic identical to 21L1. These units also provide zone 2 operation after a 250 ms delay. The zone 2 operation has not been included in this study since the delay is longer than the study time.

The reverse-looking blocking elements, designated **21L3**, are set to reach back into the protected line by 33.7Ω at 85°, and out of the protected line by 127Ω at 85°. This offset characteristic is produced by a "Load Angle Compensator", Westinghouse Canada type LAC-1H, and designated **LAC** for this study (see fig. 6). The principal function of the LAC is to ensure that the

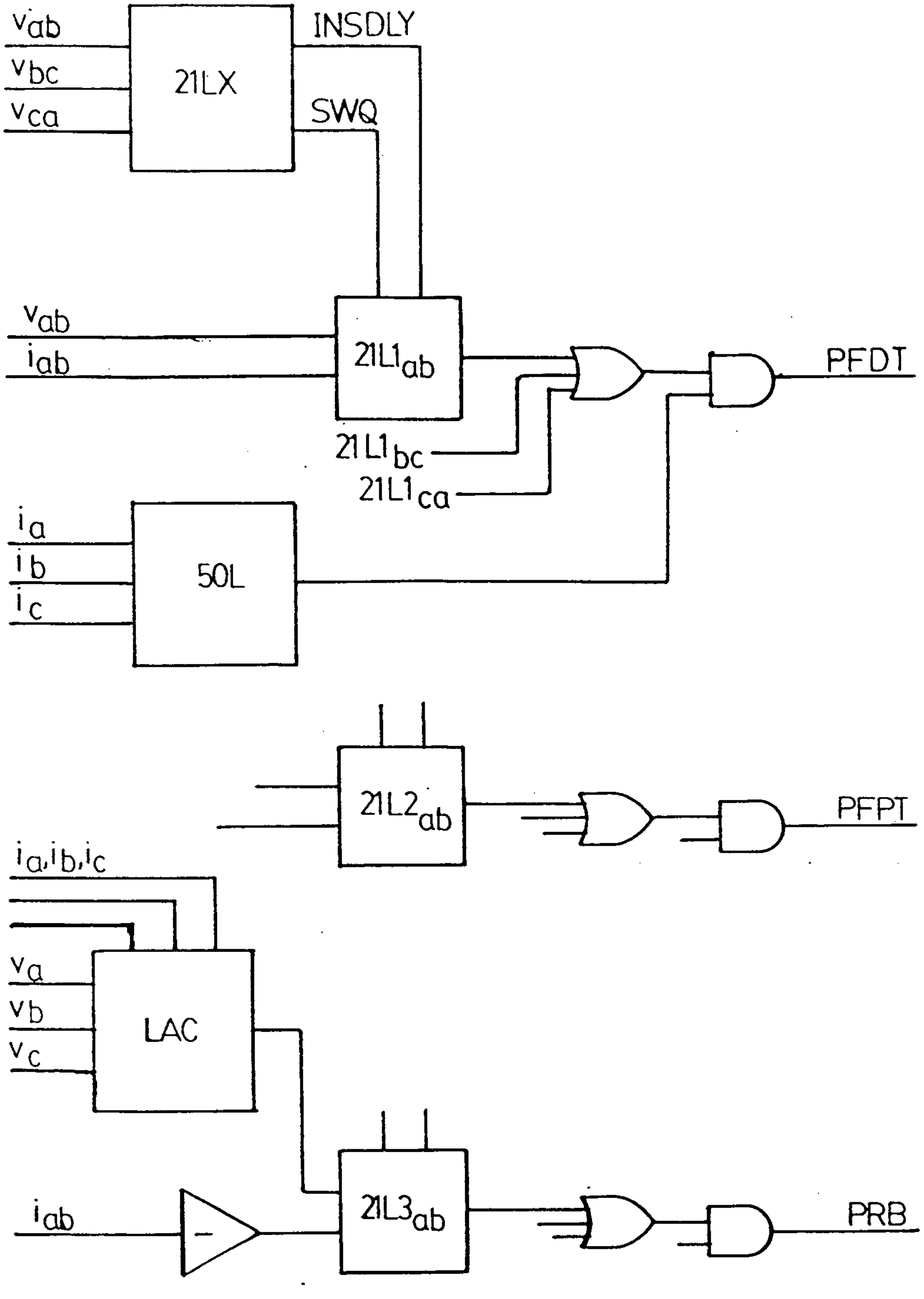


Fig. 5. Phase-fault protection (as modelled) (Signal abbreviations are defined in table 1. Relays are described in text. Inputs to 21L2 and 21L3 are similar to 21L1, except as shown.)

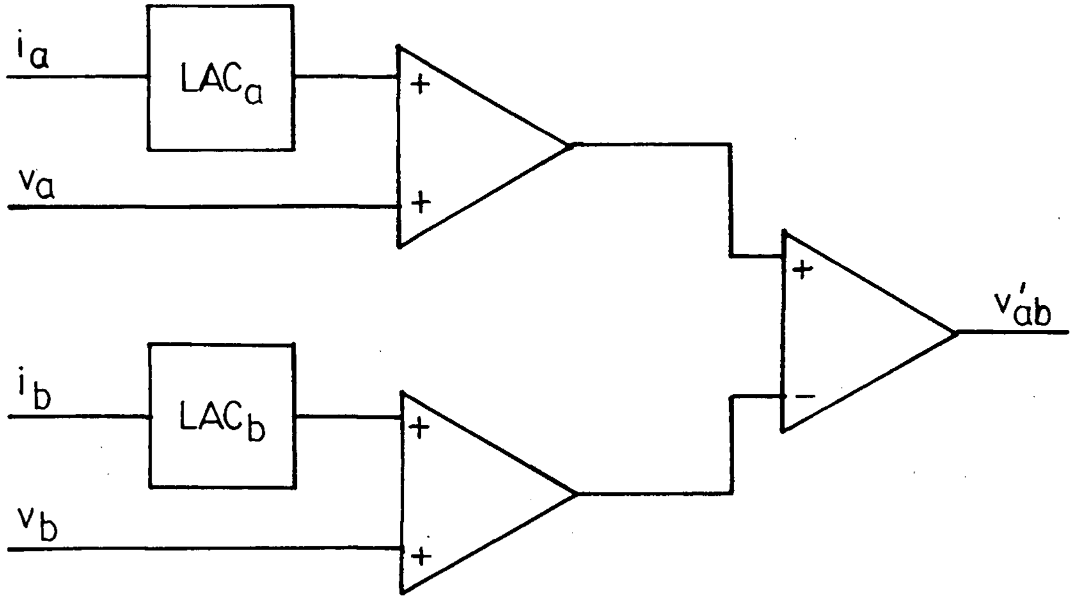


Fig. 6. Details of LAC connection for 21L3 SD-2H voltage input

transient characteristics of 21L3 coordinate with those of the remote 21L2 unit when the protected line is carrying significant pre-fault current. (Pre-fault current modifies the transient characteristic of memory-polarized mho relays.)

The LAC (which is essentially three independent transactors) uses the line currents to produce output voltages which are phase-shifted +90° with respect to the currents. The LAC output voltages are added to the input voltages of 21L3. The modified 21L3 voltages compensate for the phase angle differences between the memory voltages of 21L3 and the remote 21L2, caused by the voltage drop across the intervening line impedance. The net effect is to align the transient characteristic of 21L3 to that of the remote 21L2, thus ensuring that 21L2 will not operate for a fault beyond 21L3 which 21L3 can not see (and therefore block). A full description of the operation of the LAC is given in the manufacturer's instruction manual (Westinghouse Canada Inc., 1979).

Although the reach values are correct, the specific settings used for 21L3 and the LAC in this study are different from those used with the actual devices. The reason for this is that the burden of the 21L3 voltage circuit causes a voltage drop across the LAC, which modifies the actual characteristics from those which would otherwise be expected. The effect of the 21L3 burden is not modelled for this study, so that no compensating adjustments were needed in the settings.

All of the reach values given above have been those which apply under static conditions. The use of memory polarizing gives a characteristic which, for internal faults, is greatly expanded for a short time after fault incidence for 21L1 and 21L2, and greatly reduced for 21L3 (closure to Hayden et al., 1971).

To reduce sensitivity to transients, the SD-2H relay employs an input filter in the "IZ-V" circuit. The Q of this filter is low under normal conditions so as to avoid operating delays, which are especially severe for faults near the limit of reach due to the low operating energy then available.

Some 2-4 ms after a transient disturbance is detected, the Q of the filter is switched to a higher value, providing improved filtering against post-fault transients. To prevent misoperation caused by switching transients, a pickup delay of 35-45 ms (modelled as 40 ms) is inserted into the output of 21L1 and 21L2 (provided that they have not already operated). The delay-insertion feature is inhibited for 30-40 ms (modelled as 35 ms) after fault detection to permit rapid relay operation for true faults.

The **filter-switching** and **insert-delay** signals are provided by a fault-detecting relay, Westinghouse Canada type SDX-1H, designated **21LX.** This relay operates when a negative sequence voltage of 22.5 kV or greater (primary value) is detected, or when the primary voltage drops below 360 kV line-to-line (thus ensuring continued operation for three-phase faults).

All phase-fault relays are supervised by a three-phase, low-set line current relay set at 268 A (primary), designated **50L.** The setting is high enough to allow the relay to reset on steady-state line charging current. (For this study, 50L has been modelled as three single-phase overcurrent elements with OR-connected outputs.)

2. Ground-fault Protection

Ground wires are used only within a short distance of the substations, so that for the vast majority of ground faults, the fault resistance is determined by the tower footing resistance. The design value of fault resistance is 300Ω, although tower footing resistances of over 1000Ω have been measured.

As a consequence of the high fault resistances, residual overcurrent protection is used for ground faults. Figure 7 shows the ground fault relaying in logic-diagram form.

The principal ground overcurrent device is a Westinghouse Canada type S1G-1H positive-sequence-restrained instantaneous overcurrent relay, designated **50LN**. This device includes three independent overcurrent elements with individual setpoints (see fig. 8). The positive-sequence restraint prevents operation on load-derived zero-sequence current, such as occurs during conditions of unsymmetrical bypass of the series capacitor bank.

The high-set element, designated **50LN/IOD**, is the underreaching element

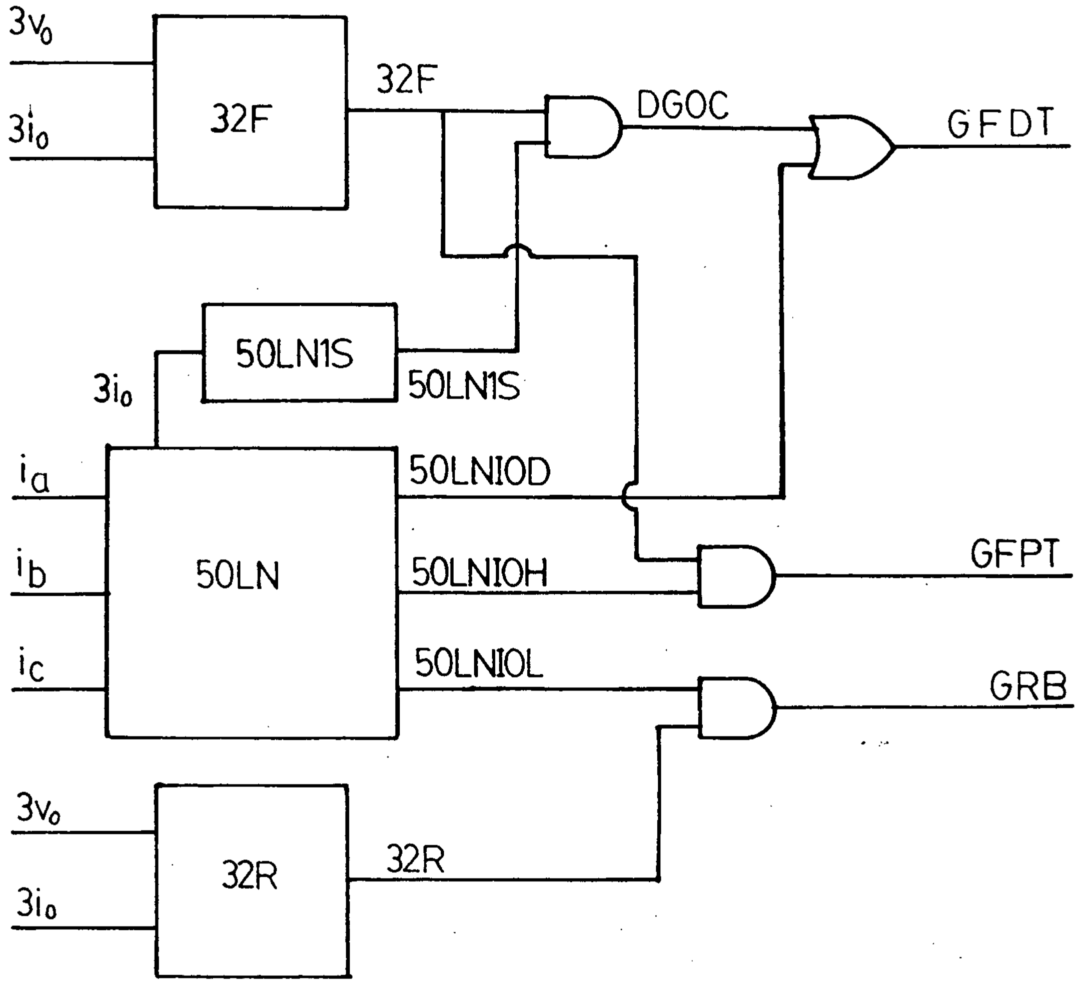


Fig. 7. Ground-fault protection (as modelled) (Signal abbreviations are defined in table 1. Relays are described in text.)

used for direct tripping in the transfer trip scheme. This element is set to pick up when

$$3|I_0| - 0.2|I_1| \geq 1400 \text{ A (primary)}$$

No directional supervision is used with 50LN/IOD.

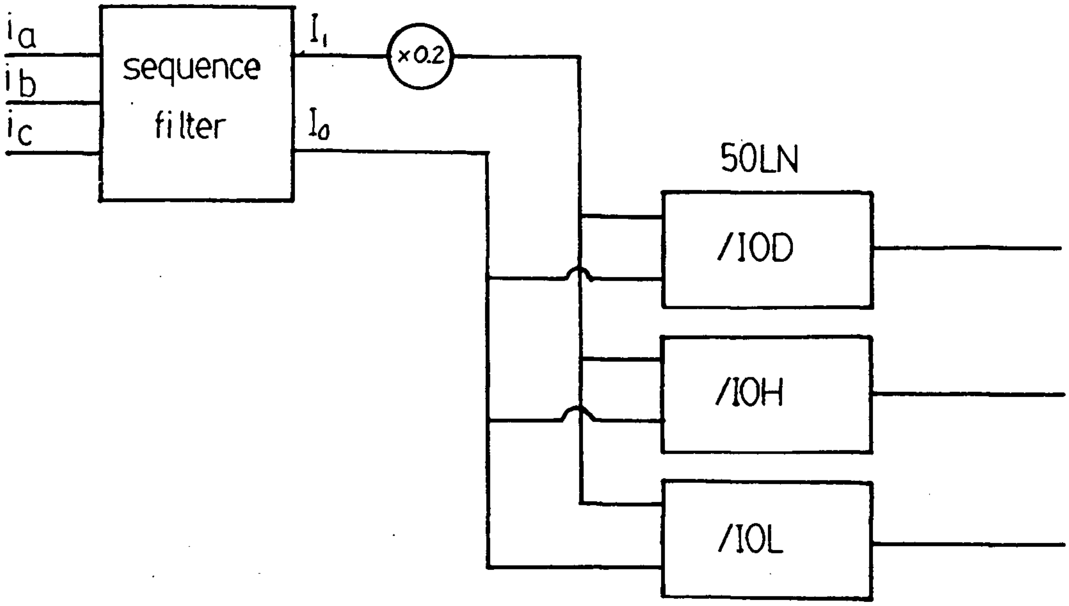


Fig. 8. Details for 50LN modelling

A second element of 50LN, designated **50LN/IOH**, is set to pick up when

$$3|I_0| - 0.2|I_1| \geq 300 \text{ A (primary)}$$

This is the overreaching element used in the permissive trip scheme, and is supervised by the forward directional element designated **32F**.

The final (low-set) element of 50LN, designated **50LN/IOL**, is set to pick up when

$$3|I_0| - 0.2|I_1| \geq 100 \text{ A (primary)}$$

This is the reverse-blocking element used in the permissive trip scheme, and is supervised by the reverse directional element designated **32R**.

The forward and reverse directional elements 32F and 32R are

Westinghouse Canada type SRG-1H devices, potential-polarized from an auxiliary transformer with a broken-delta secondary. These devices remain muted (in the unoperated state) until the input current exceeds 50 A (primary). The muting helps prevent misoperation of the permissive trip scheme due to slow reset of 32F/R.

Element 32F is set for a maximum torque angle (MTA) of -90°, with an operate zone of ±85° about the MTA. Element 32R is set to overlap 32F, with an MTA of +90° and an operate zone of ±96° about the MTA.

The directional element models which form the basis of the 32F/R models are of "infinite" sensitivity, viz. they do not require any threshold magnitude of current or voltage to operate. Consequently, the muting has been obtained by using an instantaneous overcurrent element to gate the current input to the directional elements (see fig. 9). This approximates the effect of finite sensitivity. (Note that finite sensitivity could also have been included directly in the directional element model, making external manipulation unnecessary. It was included separately here to demonstrate the technique.)

In addition to the main ground fault relaying just described, the secondary protection includes an extra inverse-time overcurrent relay, ASEA type RRIDE-41, designated **50LN1S**. This relay has a "very-inverse" characteristic with a time dial setting of 0.13, which produces a time-overcurrent curve described by

$$t = 1.8 / (I - 1) \text{ seconds,}$$

where I is the ratio of input current to setting current. The setting is 200 A (primary). This relay is directionally supervised by 32F, and operates in a direct tripping mode.

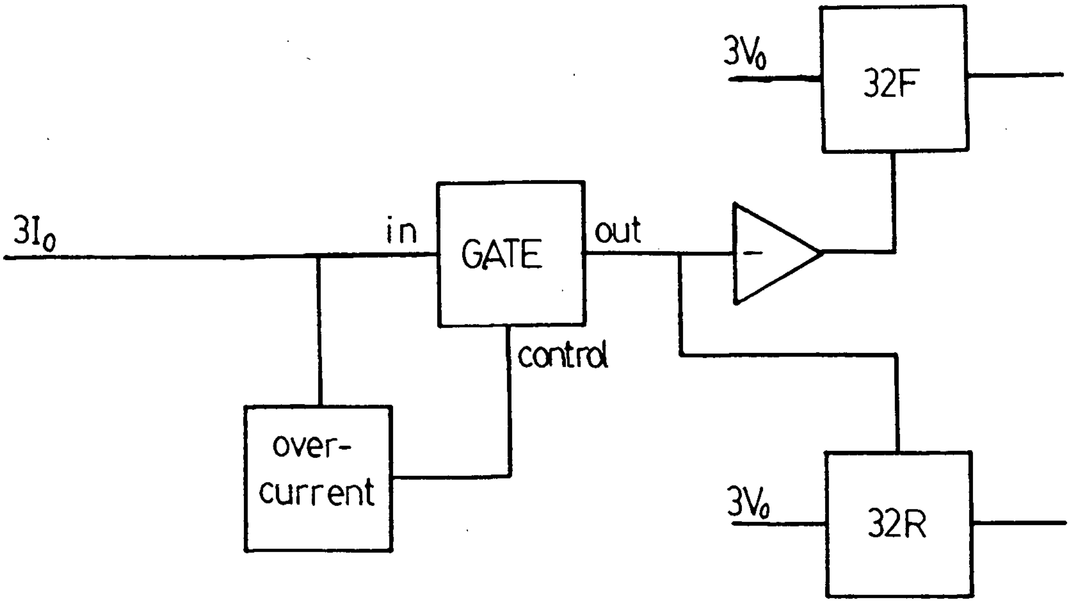


Fig. 9. Details for 32F/R modelling

The combination of phase- and ground-fault protection, shown in fig. 10, is entirely straightforward. The reverse-blocking is held, once set, for a minimum of 100 ms.

The transfer- and permissive-trip logic is shown, as modelled, in figs. 11 and 12. The Williston circuit breaker trip signal is obtained in the simulations as an OR combination of the Williston and G.M. Shrum transfer-trip outputs from the permissive trip block. The actual scheme logic generates the trip signal somewhat differently (see appendix B, part A), although the two are logically equivalent.

The transfer-trip signal is developed from the OR combination of the direct local trip (***DLT***) signal and the confirmed permissive trip. This latter signal is obtained from an AND combination of the local forward permissive (***LFP***) signal

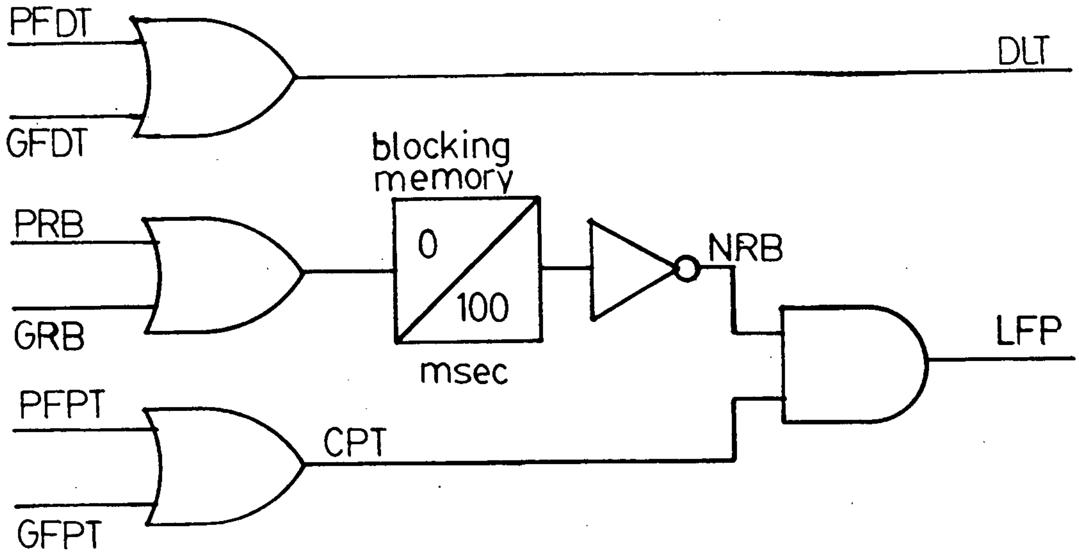


Fig. 10. Phase- and ground-fault combining logic

and the received permissive signal transmitted from the remote end (***GMS.TTT*** for Williston-end protection). (Table 1 lists the signal abbreviations used in the TRP listing in appendix B and the logic drawings.)

For increased security, the permissive trip logic incorporates three special features:

- direct local trip signals key both the permissive- and transfer-trip tones,

- when a permissive-trip situation is confirmed, a transfer-trip tone is keyed, and

- when a permissive-trip tone is received, but no local permissive

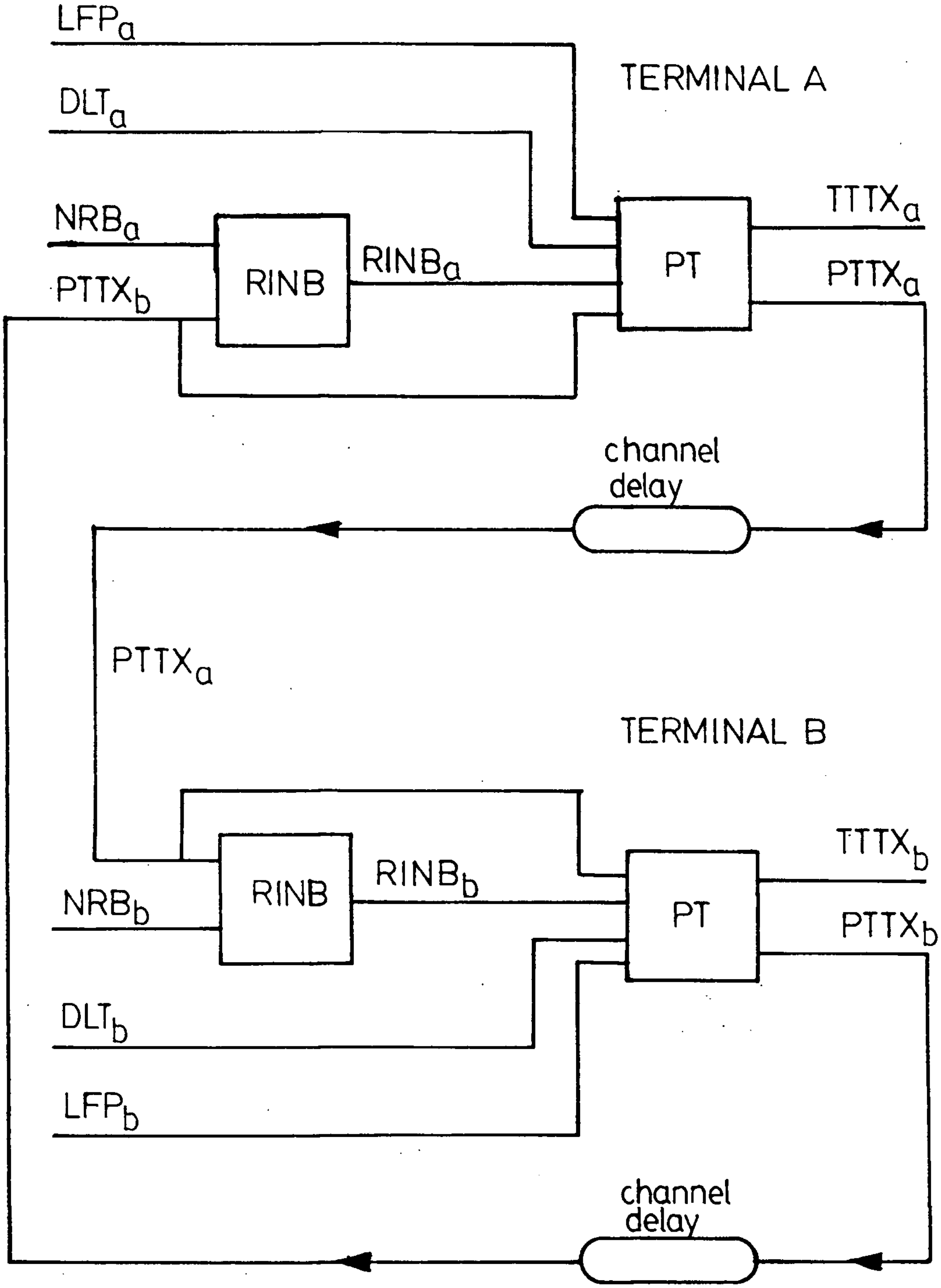


Fig. 11. General structure of permissive-trip model

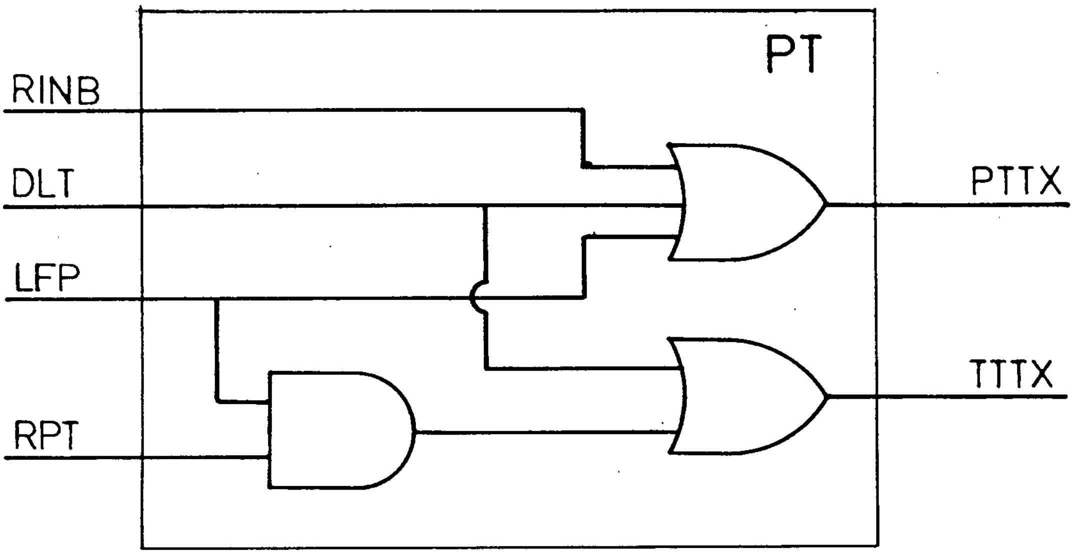


Fig. 12. Detailed structure of PT block for permissive-trip model

condition exists, the permissive tone is repeated provided no local blocking condition exists. This feature, designated **repeat-if-no-block** (***RINB***), permits relatively fast clearing for faults (particularly high-resistance ground faults) which do not create sufficient infeed from both ends of the line. Details of this feature are shown in fig. 13.

D. ASSUMPTIONS AND OPERATING CONDITIONS FOR STUDY

Frequency-dependence of the transmission-line parameters has been ignored; line constants have been computed at 60 Hz. Steady-state results should thus be correct, while aerial-mode transients should be only slightly in error.

Ground-mode transients, which are significant only for ground faults, will have insufficient damping at the higher frequencies. For relays modelled with

TABLE 1

List of Abbreviations for Simulation Waveforms

Abbreviation	Waveform
CPT	combined permissive trip (phase- and ground-overreaching
DGOC	directional ground overcurrent
DLT	direct local trip signal
FILTERX	delayed-dropout filter-switching control signal for 21L3
GATE	gating control signal for 32F/R input gate (to account for finite sensitivity)
GFDT	ground-fault direct trip logic signal
GFPT	ground-fault permissive trip logic signal
GIAB	G.M. Shrum AB delta current
GIBC	G.M. Shrum BC delta current
GICA	G.M. Shrum CA delta current
GMSDLT	G.M. Shrum direct local trip logic signal
GMSNRB	G.M. Shrum no reverse blocking logic signal
GMSLFP	G.M. Shrum local forward permissive logic signal
GMS.IA	G.M. Shrum delayed phase A current
GMS.IB	G.M. Shrum delayed phase B current
GMS.IC	G.M. Shrum delayed phase C current
GMS.TTT	G.M. Shrum transfer-trip transmit signal
GMS.VA	G.M. Shrum delayed phase A voltage
GMS.VB	G.M. Shrum delayed phase B voltage
GMS.VC	G.M. Shrum delayed phase C voltage
GRB	ground-fault reverse blocking logic signal
GVAB	G.M. Shrum delayed AB inter-phase voltage
GVBC	G.M. Shrum delayed BC inter-phase voltage
GVCA	G.M. Shrum delayed CA inter-phase voltage
G3I0	gated residual current $3I_0$ for input to 32R
IA	phase A current to LAC
IAB	AB delta current for 21L3
IB	phase B current to LAC
IBC	BC delta current for 21L3
IC	phase C current to LAC
ICA	CA delta current for 21L3
INSDLY	insert-delay control signal for SD-2H
LACA	phase A LAC output voltage
LACB	phase B LAC output voltage
LACC	phase C LAC output voltage
LFP	local forward permissive signal
NG3I0	negation of G3I0 for input to 32F
NRB	no reverse blocking logic signal
PERM	output from permissive-trip block
PFDT	phase-fault direct trip logic signal
PFPT	phase-fault permissive trip logic signal

TABLE 1 (cont'd)

PRB	phase-fault reverse blocking logic signal
PSFILTER	positive-sequence filter output
PT	permissive trip
PTTX	permissive-trip transmit signal
RB	reverse blocking logic signal
RESTRAIN	positive-sequence restraining voltage for 50LN
RINB	repeat-if-no-block logic signal
RPT	received permissive trip signal
SWQ	Q-switching control signal for SD-2H
TMP	temporary (intermediate waveform)
TMP0	temporary (intermediate waveform)
TMP1	temporary (intermediate waveform)
TTTX	transfer-trip transmit signal
VA	phase A input voltage for 21L3 after inclusion of LAC output
VB	phase B input voltage for 21L3 after inclusion of LAC output
VC	phase C input voltage for 21L3 after inclusion of LAC output
VAB	AB inter-phase voltage for 21L3
VBC	BC inter-phase voltage for 21L3
VCA	CA inter-phase voltage for 21L3
WIAB	Williston AB delta current
WIBC	Williston BC delta current
WICA	Williston CA delta current
WSNDLT	Williston direct local trip logic signal
WSNLFP	Williston local forward permissive logic signal
WSNNRB	Williston no reverse blocking logic signal
WSN.CB	Williston circuit breaker trip signal
WSN.TTT	Williston transfer-trip transmit signal
WVAB	Williston AB inter-phase voltage
WVBC	Williston BC inter-phase voltage
WVCA	Williston CA inter-phase voltage
3I0	residual current $3I_0$
3V0	residual voltage $3V_0$
21LX	21LX outputs
21L1	21L1 output
21L1AB	21L1 "phase" AB element output
21L1BC	21L1 "phase" BC element output
21L1CA	21L1 "phase" CA element output
21L2	21L2 output
21L2AB	21L2 "phase" AB element output
21L2BC	21L2 "phase" BC element output
21L2CA	21L2 "phase" CA element output
21L3	21L3 output
21L3AB	21L3 "phase" AB element output
21L3BC	21L3 "phase" BC element output
21L3CA	21L3 "phase" CA element output

TABLE 1 (cont'd)

32F	32F forward directional element output
32R	32R reverse directional element output
50L	50L distance supervision overcurrent output
50LA	50L distance supervision phase A output
50LB	50L distance supervision phase B output
50LC	50L distance supervision phase C output
50LNIOD	50LN ground overcurrent direct trip output
50LNIOH	50LN ground overcurrent permissive trip output
50LNIOL	50LN ground overcurrent blocking output
50LN1S	50LN1S secondary ground overcurrent output

filters in the input circuits (such as the directional elements), the effect on operation will be minimal. There should also be little effect on the ground-fault overcurrent relay models since the amplitude comparators used are of the integrating type, which are less sensitive to higher frequencies. Thus the overall protection performance should not be seriously affected by the constant-parameter modelling.

The generator models are E'' behind L_d'' Thevenin equivalents. The effect on transients will likely be small, since this assumption is reasonably accurate for the short time span over which transients are significant. There may be some error at G.M. Shrum due to the fact that the fast static exciters have been neglected.

The G.M. Shrum braking resistance has been ignored. Since this only comes into action at fault clearing, it will affect only the fault-clearing simulation, case **H09002**.†

The operating conditions for the simulations correspond to heavy load conditions for the Peace River system. The corresponding loading on 5L1 is 1200 MVA at a 95% power factor (as measured at the G.M. Shrum end).

†The various simulations are described in chapter VI.

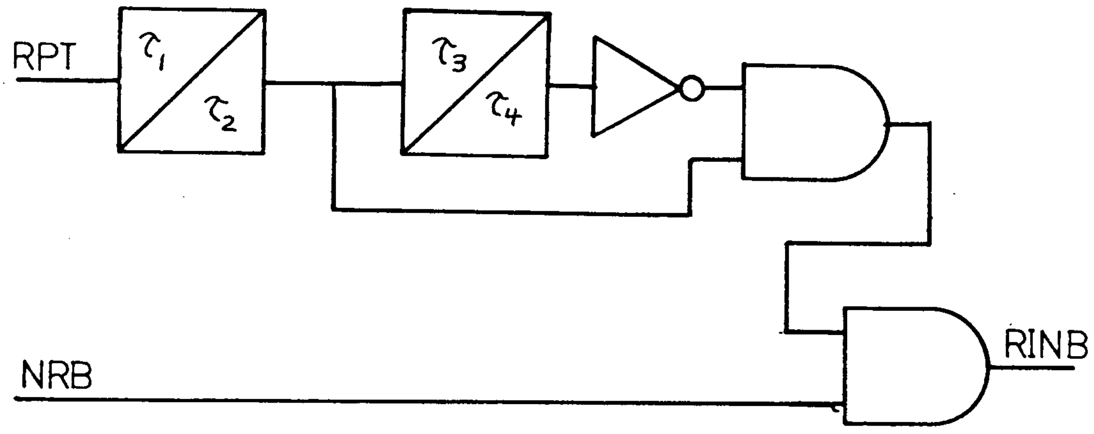


Fig. 13. Repeat-if-no-block detail for permissive-trip model

The simulations are benchmark tests, intended to exercise key portions of the protection rather than reproduce some observed operating conditions. Consequently, fault resistance has been ignored for inter-phase faults, and for all ground faults near stations. This is a natural limiting case, and gives the worst-case fault conditions (maximum voltage transient, maximum fault current, and maximum time constant for the transient components of the fault current). It also results in the minimum self-polarizing voltage for the mho relays, ensuring maximum dependence on memory polarizing.

The high tower footing resistance experienced on the Peace River system limits sensitivity to ground faults remote from the substations. Since this presents a performance limit for the ground protection (and was a major factor in the scheme design), a linear resistance of 250Ω has been used for remote ground faults. The effect of ignoring the nonlinear effects of arc voltage should be insignificant compared with the voltage developed across the 250Ω resistance. This is consistent with the recommendations of the IEEE Power System Relaying Committee (1985).

The microwave channel delay between G.M. Shrum and Williston is taken to be 9 ms.

The principal relays (SD-2H distance relays for phase faults, and 50LN restrained-overcurrent relay for ground faults) have been modelled using specific relay models. The remaining models (e.g. the 50L current supervisory relay, 32F/R directional relays) are generic (see chapter IV). The use of generic modelling for these less-important relays eliminated the need for detailed knowledge about the relays, and the dedication of a substantial amount of time to the preparation of special models. The use of generic modelling for the less-critical relays is not expected to adversely affect the simulation results.

The instrument transformers have not been modelled; the effect of their omission is discussed in the following subsection.

1. Effects of Not Modelling Instrument Transformers

One reason for ignoring the instrument transformers for this study is that the modelling of instrument transformers for transient simulations has received thorough study elsewhere (Wong and Humpage, 1978; Krishnamoorthy and Venugopal, 1974; Wright and Rhodes, 1974; Germay et al., 1974). It was considered unnecessary to complicate this study by including the extra detail.

There are also good reasons to expect that the instrument transformer effects, described in detail in chapter IV, will not be of serious concern for the simulations described herein:

a. Current transformers

None of the three principal causes of measurement error due to current transformers are of major concern for the studies described herein. Core saturation, the first of these causes, is unlikely to cause serious errors since the CTs were originally specified to produce no more than 10% ratio error under worst-case conditions (Hayden et al., 1971).

The second principal cause of CT measurement error, the relaxation transients which arise when the CT primary current is suddenly interrupted, also should not be of concern for the simulations considered here. The only situation which can cause a complete collapse in primary current is the clearing of 5L1, which does not occur in these simulations. (Load currents should mask the relaxation transients for case **H09002**, in which a 5L2 fault is cleared.)

The third principal cause of CT measurement errors, limited frequency bandwidth, would not present a serious source of error even if it were as low as the 1 to a "few thousand" Hertz given by Chamia (1980). This is particularly so when the effects of input filters, used on all of the principal relays, are taken into account.

b. Capacitive voltage transformers

Neglecting ferroresonance, which can be prevented by correctly sizing the core of the internal magnetic VT, there are two remaining major causes of measurement errors due to capacitive voltage transformers. Relaxation transients, the first of these, are unlikely to cause serious errors for this study due to the memory polarization of the distance relays. The relaxation transients arise when a fault occurs close to the CVT location, causing the primary voltage to collapse suddenly. The memory polarizing of the SD-2H ensures that the relaxation transients are insignificant with respect to the total polarizing voltage applied to the phase comparator. (Since the current is high in the "IZ-V" input circuit under fault conditions, CVT relaxation transients are not significant for this input either.)

The second principal cause of CVT measurement errors, limited bandwidth, would seem the most likely to affect relay operation. For the principal relays, however, the 20 to a "few hundred" Hertz range given by Chamia (1980) is less likely to limit signals applied to the relay measuring circuitry than are the high-Q input filters and memory circuits. This effect too, then, can reasonably be ignored for the benchmark simulations used herein.

Tests conducted by Hayden et al. (1971) proved that "CVT performance would not jeopardize the relay operation", supporting the above statements.

2. Use of Transient Response Processor for Protection Simulation

The Transient Response Processor (TRP), described in some detail in appendix C, provides a powerful tool for the simulation of protection schemes under transient conditions. Input data (power system transient responses, generally) can be from any source, the only requirements being that the data be complete (i.e. no missing pertinent information) and digitized. Typical sources would be digital simulation programs (such as the widely-popular EMTP used for this study) or digitized Transient Network Analyser (TNA) waveforms or fault recordings.

The design of the TRP is such that, with the provision of suitable library software (**user functions**), the TRP command language can serve as a high-level simulation language. This feature has been used, along with a comprehensive library of protective relay models, to permit the TRP to function as a sophisticated transient protection simulator.†

A number of TRP user functions have been added to allow modelling the protection. Two types of functions have been provided:

- **processing** functions to provide the logical operations AND, OR, and NOT, and

- **model** functions which simulate an RLC filter, delayed pickup/dropout timer, positive-sequence filter, the permissive-trip logic (including the transfer-trip logic, since the two are cross-coupled in the Peace River scheme), load-angle compensator, and the directional, inverse-time overcurrent, instantaneous overcurrent (obtained as an option of the inverse-time overcurrent model), restrained overcurrent, SDX-1H, and SD-2H relays and relay elements.

Two approaches have been used with the **model** functions. In some cases (e.g. SD2H, SDX1H) the TRP function represents a complete relay. This approach has generally been taken only for very specific models. In the remaining cases (e.g. directional units 32F/R, ground fault relays 50LN) the TRP function represents only a portion of the relay, several functions being used for a complete model. This approach has the advantage of flexibility, and minimizes the number of special-purpose functions required, since functional equivalents of

†While intended for use with digital models of relays and transducers, the TRP design permits analog devices to be substituted for the digital models, provided, of course, that suitable hardware (reasonably high-speed digital-to-analog and analog-to-digital converters, wide-bandwidth high-power amplifiers, etc.) is available. This feature was not used for this research.

specific relays can be built up of standard functions. The first approach, however, offers the greatest clarity of the final protection "program".

Individual descriptions of the special TRP functions and details of the **model** functions may be found in appendix B. The values of the parameters used for the various relay models are listed in table 2.

3. Establishing Values for Unknown Relay Parameters

When collecting data for practical studies, it is inevitable that utility protection engineers will be confronted with some relay parameters which are not known. Where the needed information can be readily determined from instruction manuals or similar sources, this is certainly the best solution. Where the information cannot be obtained, however, it must be estimated with the aid of test simulations. (This is necessarily the case when doing simulations for protection planning, before the protection design has been finalized.) For the simulations reported herein, test simulations were required to estimate memory and filter Q values for various relays.

When testing for the memory and filter Q values, it was decided that they should be made no greater than was absolutely necessary to obtain correct protection performance. Test simulations showed that the directional element (32F and 32R) input filters needed a minimum value of Q=1 to reduce the "dithering" (characteristic of block-average phase comparators subjected to high frequency transients) to acceptable amounts. Similarly, the zero-sequence filters in the ground-fault overcurrent relays were found to require a minimum value of Q=1 to prevent serious transient overreach.

An interesting problem arose with the SD-2H model during tests to find

TABLE 2

Parameter Values for Relay Models

(Values are the same at both Williston and G.M. Shrum)
(Unspecified values are model defaults)

Relay	TRP Model	Parameter	Value
21LX	SDX1H	primary phase-to-phase undervoltage setting	360 KV
		primary negative sequence voltage setting	22.5 KV
		undervoltage sequence hysteresis	33%
		negative sequence hysteresis	33%
21L1	SD2H	replica impedance	35.4Ω
		replica impedance angle	85°
		input filter high-Q value	10
		input filter low-Q value	1
		memory Q value	5
		delay	40 ms
		phase-coincidence angle	82.5°
		hysteresis level	33%
21L2	SD2H	replica impedance	123Ω
		replica impedance angle	85°
		input filter high-Q value	10
		input filter low-Q value	1
		memory Q value	5
		delay	40 ms
		phase-coincidence angle	82.5°
		hysteresis level	33%
21L3	SD2H	replica impedance	160.7Ω
		replica impedance angle	87.1°
		input filter high-Q value	10
		input filter low-Q value	1
		memory Q value	5
		delay	none
		phase-coincidence angle	82.5°
		hysteresis level	33%
	TIMER	Filter dropout delay	60 ms
		Filter pickup delay	none
LAC	LAC	impedance setting	33.77Ω
50L	OVERCURRENT.IT	primary pickup setting	268 A
		time-multiplier setting	1
		hysteresis level	33%
32F	DIRECTIONAL	$3V_0$ filter Q	1
		$3I_0$ filter Q	1

TABLE 2 (cont'd)

		maximum torque angle	-89.5°
		operating zone	85°
		hysteresis level	33%
	OVERCURRENT.IT	primary pickup setting	50 A
		time-multiplier setting	1
		hysteresis level	none
32R	DIRECTIONAL	$3V_0$ filter Q	1
		$3I_0$ filter Q	1
		maximum torque angle	-89.5°
		operating zone	96°
		hysteresis level	33%
	OVERCURRENT.IT	primary pickup setting	50 A
		time-multiplier setting	1
		hysteresis level	none
50LN1S	OVERCURRENT.IT	primary pickup setting	200 A
		time-multiplier setting	1000
		hysteresis level	33%
50LN/IOD	OVERCURRENT.R	positive sequence restraint factor	0.2
		primary pickup setting	1400 A
		maximum restraining amplitude	630 A
		hysteresis level	33%
50LN/IOH	OVERCURRENT.R	positive sequence restraint factor	0.2
		primary pickup setting	300 A
		maximum restraining amplitude	630 A
		hysteresis level	33%
50LN/IOL	OVERCURRENT.R	positive sequence restraint factor	0.2
		primary pickup setting	100 A
		maximum restraining amplitude	630 A
		hysteresis level	33%
blocking	TIMER	pickup delay	none
memory timer		dropout delay	100 ms
channel delay	DELAY	delay amount	9 ms
permissive-trip logic	PERMISSIVE	All values are model defaults	

Q values for the memory and "IZ-V" input filter. The memory Q had been set just large enough ($Q_M=5$) to ensure relay operation for close-up forward faults, and relay blocking for close-up reverse faults. The "IZ-V" input filter Q was similarly set just large enough ($Q_H=10$) to prevent the zone 1 underreaching elements from operating for bolted faults at the remote-end bus (due mainly to series capacitor transients).

Ordinarily these values would be expected to produce correct transient coverage of the remote side of the series capacitors at Kennedy, due to the expanded mho characteristic of memory-polarized relays under transient conditions (closure to Hayden et al., 1971). The high-Q of the "IZ-V" input filter, however, was found to produce such a strong memory effect that the polarizing-input memory was rendered largely ineffective. Further testing showed that the memory Q had to be increased to 50 (for an "IZ-V" filter value of $Q_H=5$) in order to ensure transient coverage for the remote side of the Kennedy capacitors.

The values finally used for the simulations were $Q_M=5$ and $Q_H=10$. These values would not have been adequate in the case of a multi-phase fault at Kennedy north, since the Williston zone 1 protection would then incorrectly operate. It was not necessary to study this fault here, however,† and for the corresponding Kennedy south fault, the bypassing of the series capacitors pushed the fault beyond the reach of the G.M. Shrum zone 1 relays anyway.

This experience demonstrates the importance of either transient testing or

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†It might be asked why values were not chosen which were high enough to guarantee correct behaviour for the Kennedy north fault as well. The reason is that the necessary values looked to be unreasonably large, and there was no information as to the "correct" Q values (the manufacturer's literature does not specify the values for the actual relays, and measurements were not practical). This shows the weakness of a purely empirical approach, and the importance of using any other sources of data which may be available.

transient simulation for proving the performance of relays using memory polarizing.†

The value of 630 A used for the maximum restraining amplitude for 50LN (/IOD, /IOH, and /IOD) is 20% of the maximum positive-sequence current which could flow on 5L1 for a 500 kV sending-end voltage (i.e. into a three-phase short circuit at the receiving end). Testing showed this value would produce relay operating times consistent with the specifications for 50LN.

†The same statement can probably be made for any externally-polarized mho relays, but the author has no experience to support this.

CHAPTER VI. PEACE RIVER SIMULATION RESULTS

The simulations described in this chapter are selected benchmark cases for the Peace River protection. There are four principal cases:

H09002—external A-phase SLG fault at the Williston end of 5L2, including clearing of 5L2.

H09003—internal A-phase SLG fault on the north side of Kennedy series capacitor bank.

H09012 and H11002—internal AB phase-to-phase fault on the south side of Kennedy series capacitor bank.

H10006—external AC phase-to-phase fault on the Williston bus.

Both full and reduced system models (see appendix A) have been used for the simulations. Cases H10006 and H11002 use the reduced system model with the equivalent south of Williston. The other cases all use the full system model. Simulation results for the two models are compared (for cases H09012 and H11002) at the end of the chapter.

1. Description of Benchmark Cases

The faults in the benchmark cases were applied at a **point-on-wave** angle† of 143°, referenced to the fault location phase-to-ground voltage for SLG faults, or phase-to-phase voltage for inter-phase faults. This angle has the

†Angle specifications used herein are based on the use of a cosine source function (some authors use sine sources).

advantage of simultaneously producing a current offset of approximately $-\sin(143°) \times 100\% = -60\%$ and a voltage transient of $-\cos(143°) \times 100\% = 80\%$ (of the peak pre-fault voltage).

The fault is purposely placed on the leading (rising) edge of the voltage waveform so as to be physically-plausible. Faults due to flashovers are most likely to occur during portions of the voltage cycle where the voltage is increasing, and within some 45° of voltage maximum (Warrington, 1968, pp. 205-7). The value of 143° used herein satisfies these requirements while producing relatively high values of both voltage and current transients.

The hysteresis level for all relay models has been set at 1/3 of the maximum output range. The effect of the hysteresis can be seen from comparison of fig. 14(a) and (b), which are for identical situations (behaviour of Williston ground-fault protection during a phase-A SLG bus fault at G.M. Shrum) except for relay hysteresis (also note the difference in scales). For the no-hysteresis case of fig. 14(a), the waveforms cross smoothly through the threshold at zero. For the hysteresis case of fig. 14(b), the waveforms jump suddenly (when the hysteresis comes into action) as they cross the threshold. Note also that hysteresis tends to maintain a state for a longer period of time (this is how hysteresis prevents "chattering" and improves noise immunity) so that the hysteresis and no-hysteresis waveforms may exhibit significant differences after the first threshold crossing.

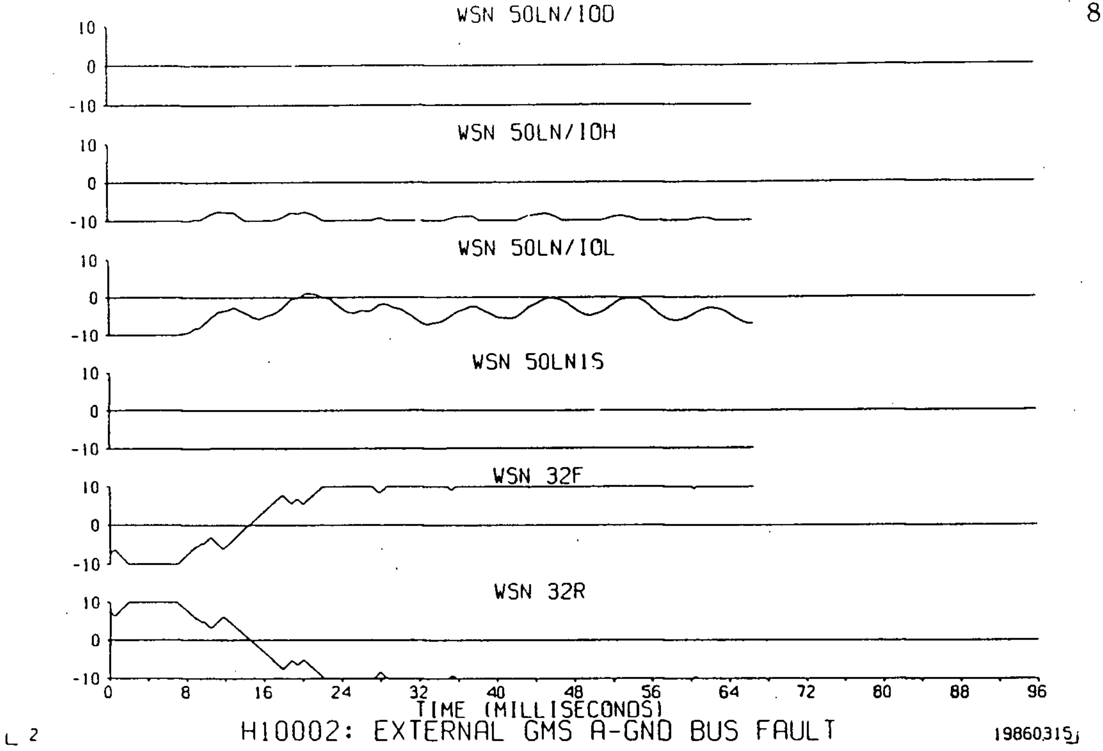

Fig. 14(a). Ground-fault protection waveforms with no relay hysteresis.

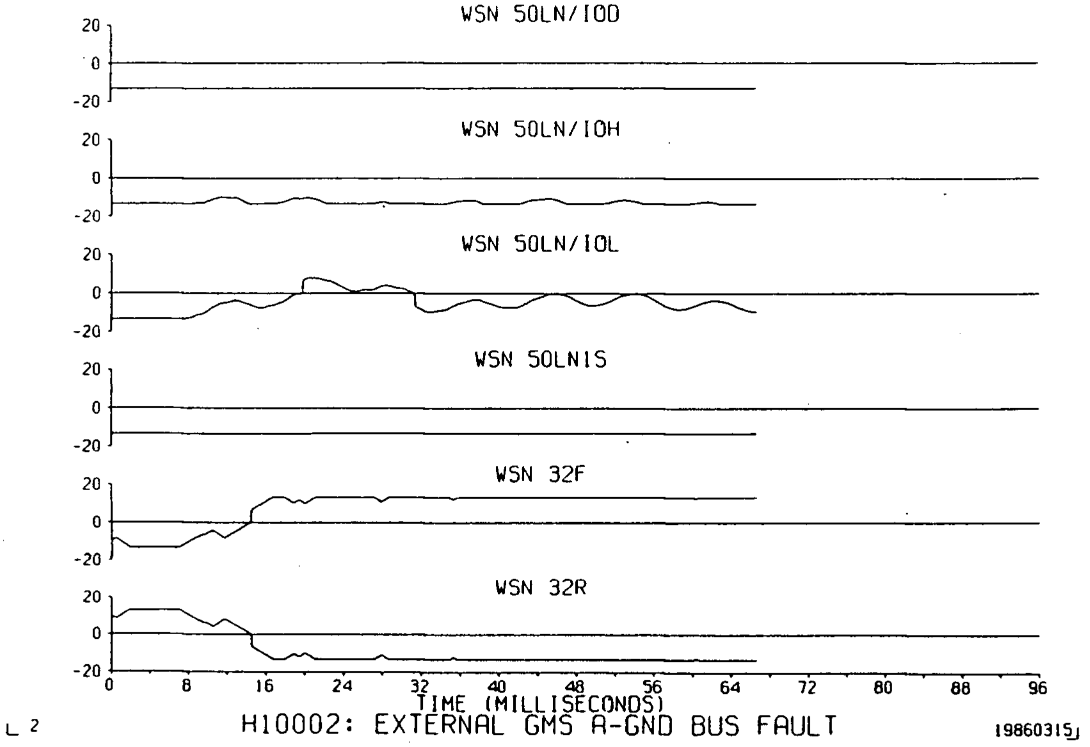

Fig. 14(b). Ground-fault protection waveforms with hysteresis.

Fig. 14. Example showing effect of hysteresis on relay output

a. Case H09012

Case H09012 is for an internal AB phase-to-phase fault on the south side of the Kennedy series capacitor bank. The large power system model was used for this simulation. The fault was applied 3.78 ms after the start of the simulation. This corresponds to a point-on-wave angle of 143°, referenced to the voltage between the faulted phases, measured at the fault location. Fault resistance is ignored.† The 5L1 series capacitor protective gaps flash at 9.2 ms.

The protection waveforms are shown in fig. 15(a-j). Referring to fig. 15(a), the Williston fault-detecting relay 21LX responds with a high output for the SD-2H Q-switching control signal within 3 ms of the fault, followed 35 ms later by a high output for the SD-2H pickup-delay-insertion control signal.

Relays 21L1 and 21L3 remain quiescent, since the fault is a forward fault and outside of the zone 1 (direct-trip) reach. The measurement ripple can be clearly seen in the 21L3 output waveform, but at all times is well below the threshold, indicating no tendency toward false blocking on transients.

The overreaching distance relay 21L2 picks up 20 ms after the fault, which is within the zone 2 reach. The clean step in output as the threshold is crossed is due to the effect of hysteresis.

The distance supervision relay 50L remains high on load and fault current throughout.

Referring now to fig. 15(b), all ground-fault relays (50LN/IOD, /IOH, and /IOL; and 50LN1S) correctly remain quiescent. (The directional elements 32F/R thus are inconsequential.)

†Note that for this fault the arc resistance would be approximately 3-6 Ω by Warrington's formula—this is comparable with the resistance of about 6 Ω due to the line itself.

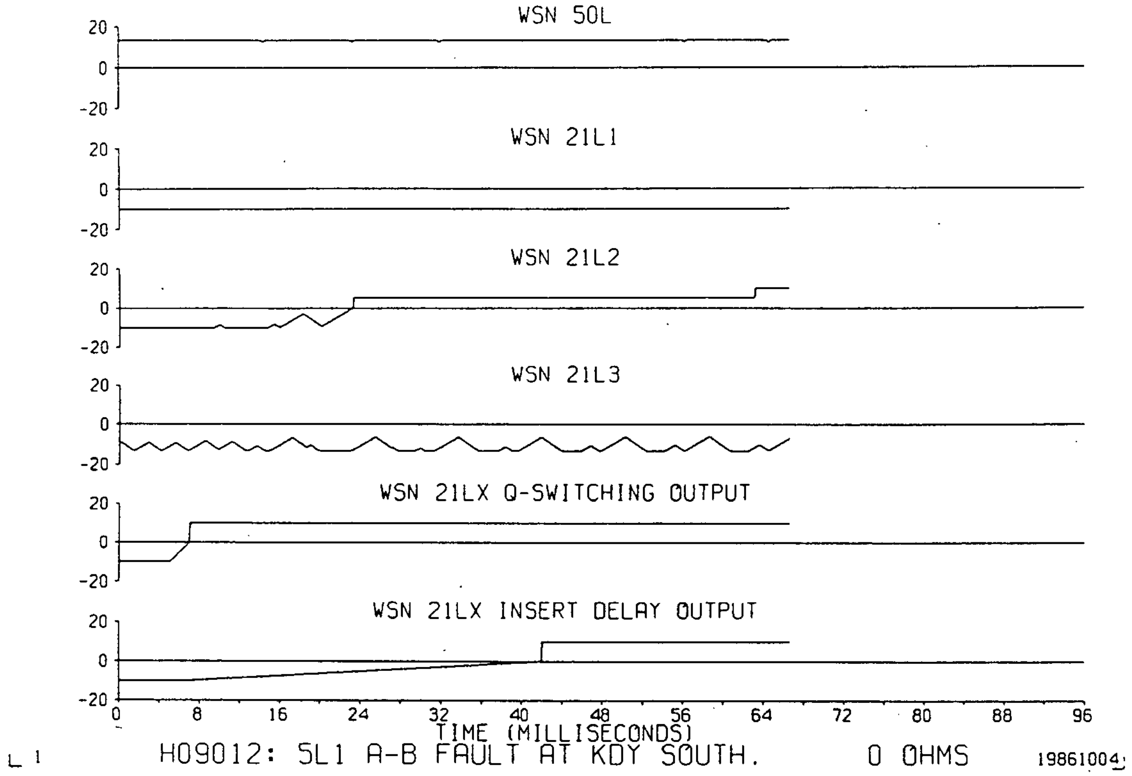

Fig. 15(a). Williston phase-fault protection waveforms

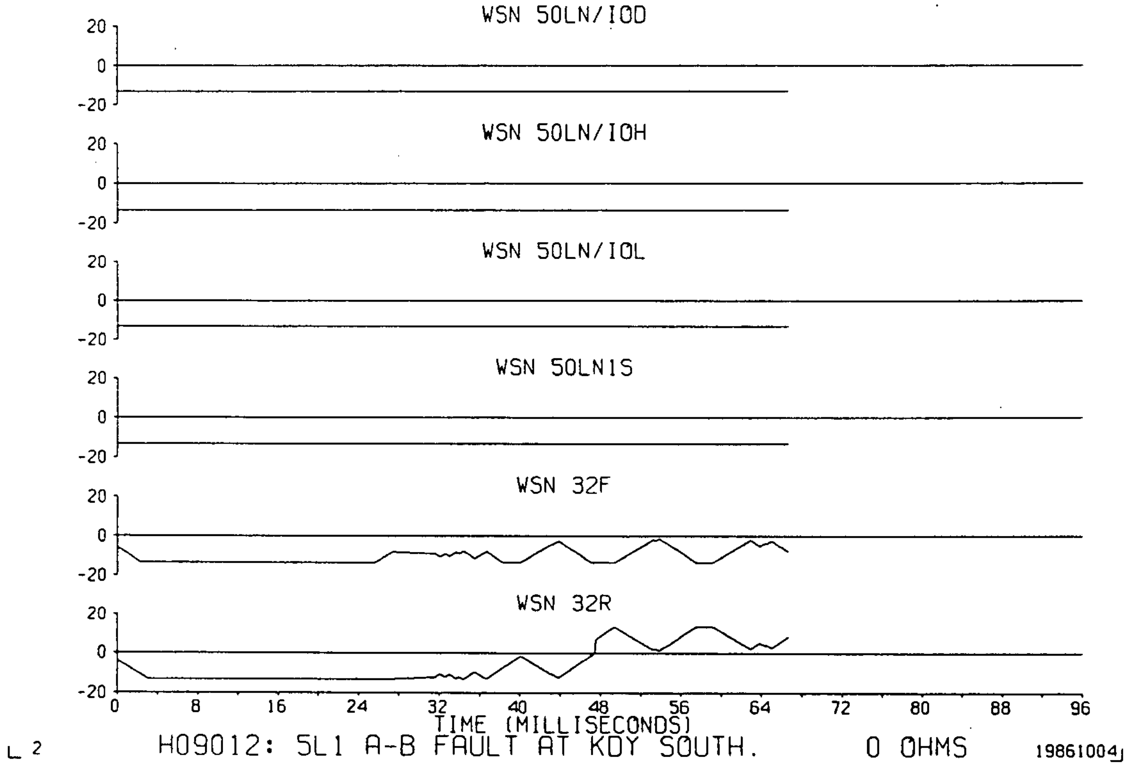

Fig. 15(b). Williston ground-fault protection waveforms

Fig. 15. Protection waveforms for case H09012

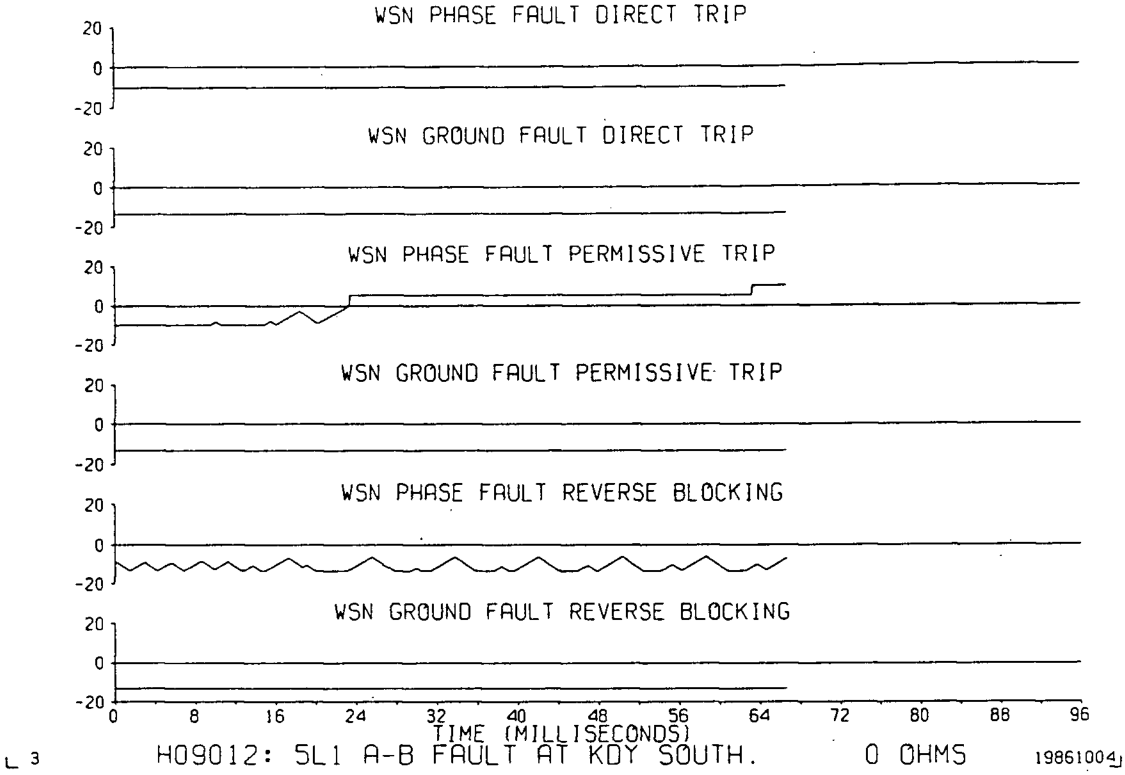

Fig. 15(c). Williston phase- and ground-fault direct, permissive, and blocking signals

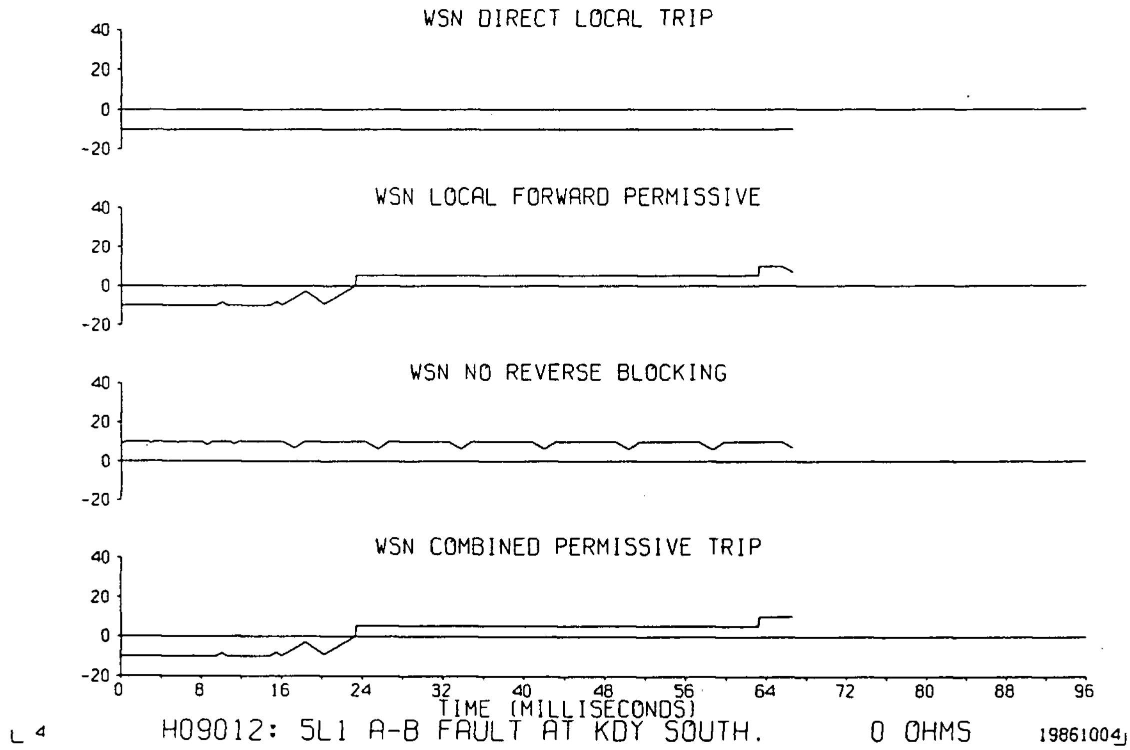

Fig. 15(d). Williston local reverse blocking and direct- and permissive-trip signals

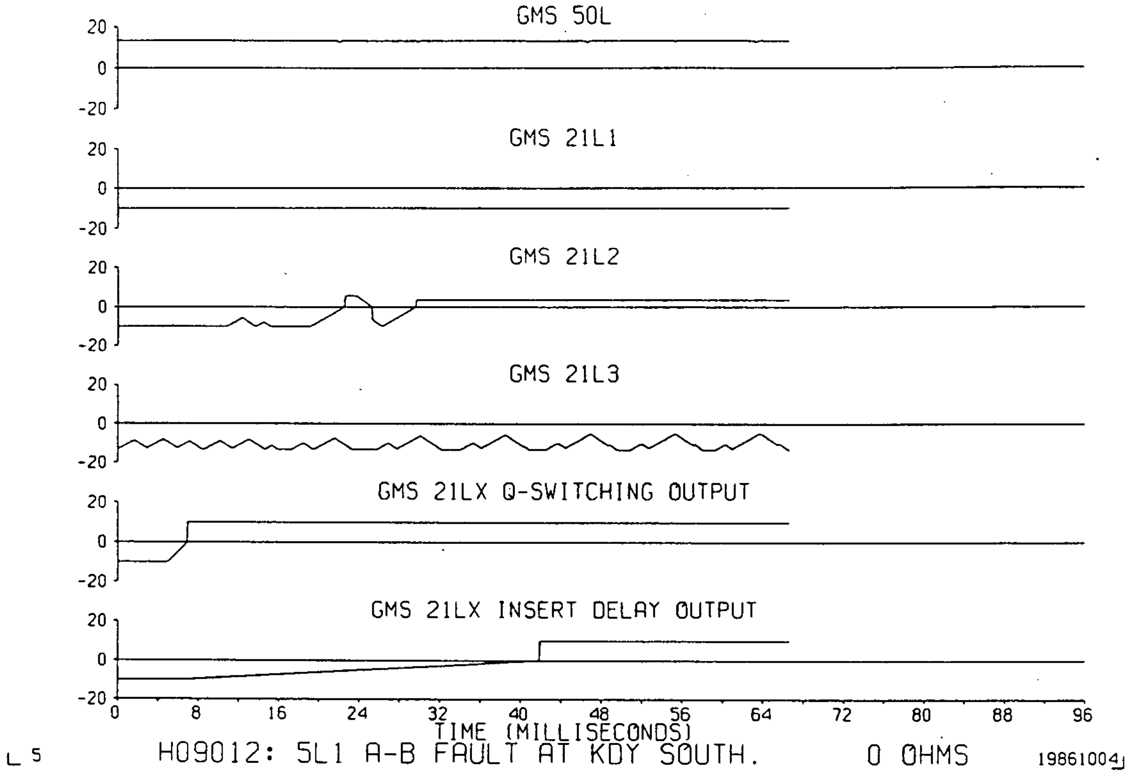

Fig. 15(e). G.M. Shrum phase-fault protection waveforms

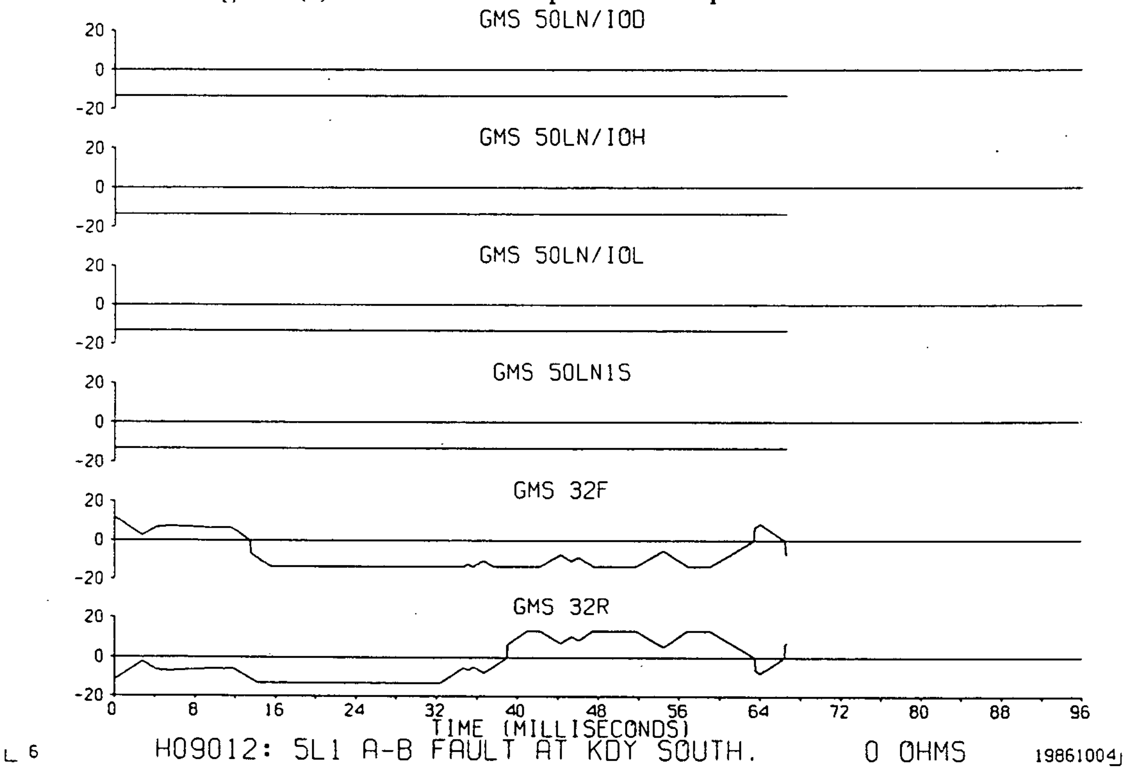

Fig. 15(f). G.M. Shrum ground-fault protection waveforms

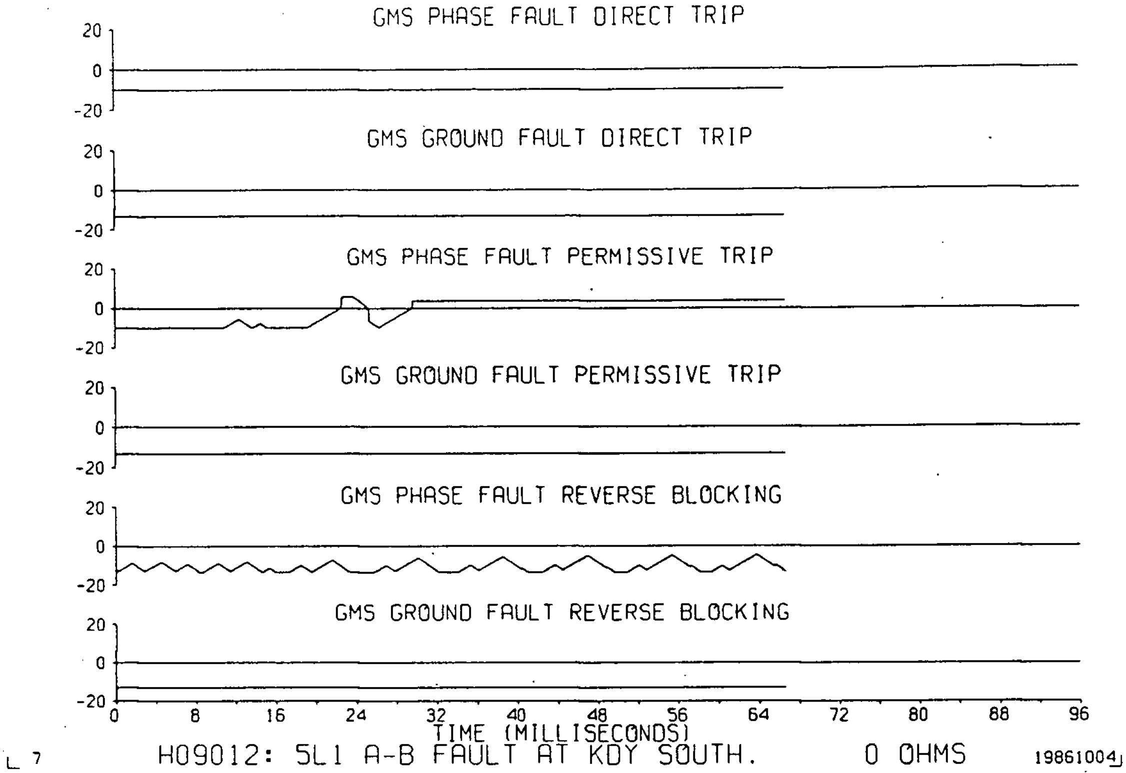

Fig. 15(g). G.M. Shrum phase- and ground-fault direct, permissive, and blocking signals

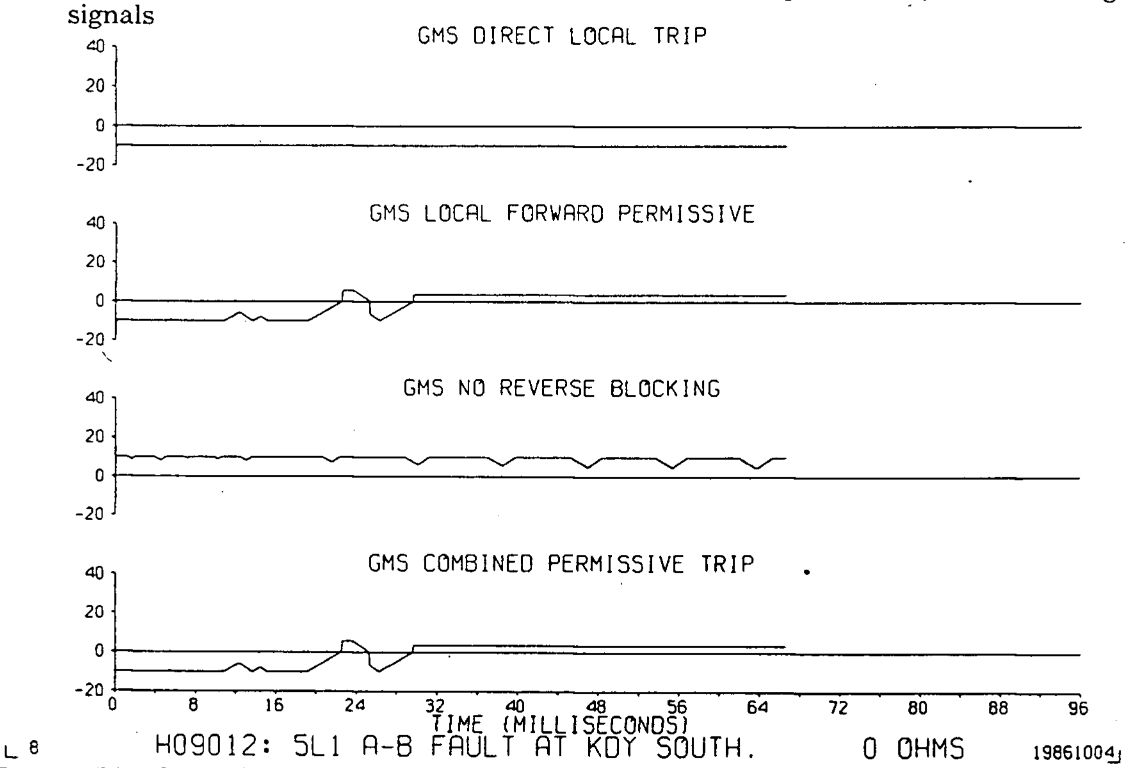

Fig. 15(h). G.M. Shrum local reverse blocking and direct- and permissive-trip signals

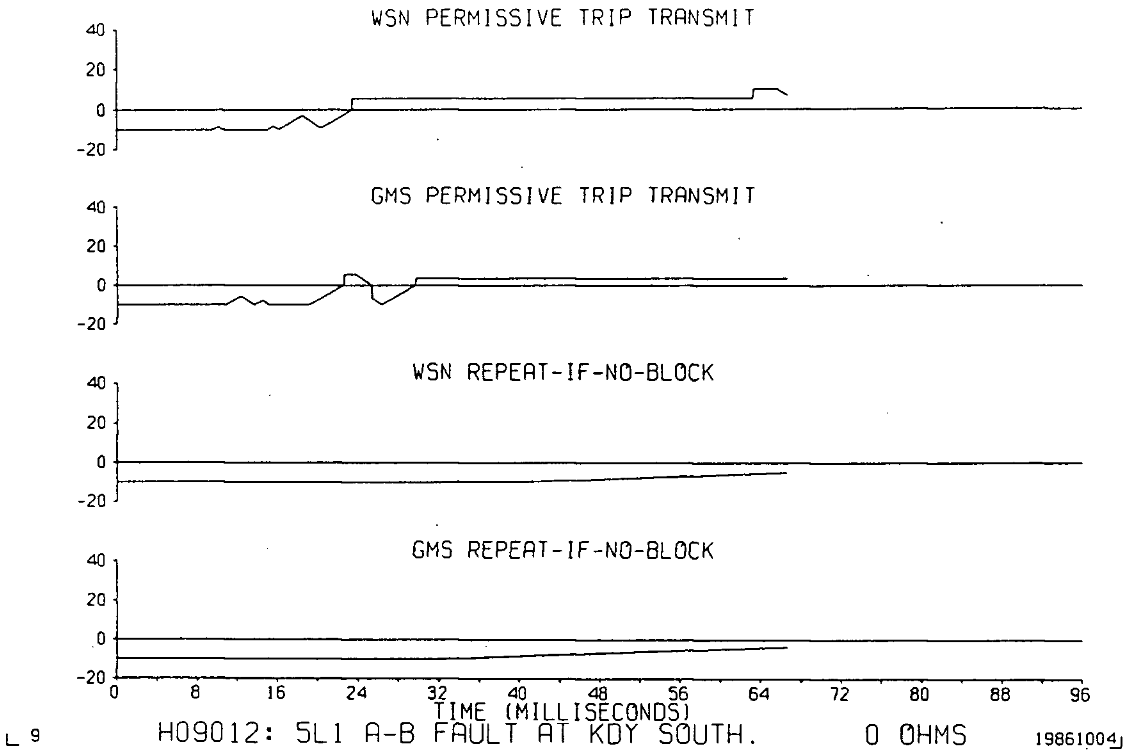

Fig. 15(i). Permissive trip and repeat-if-no-block waveforms

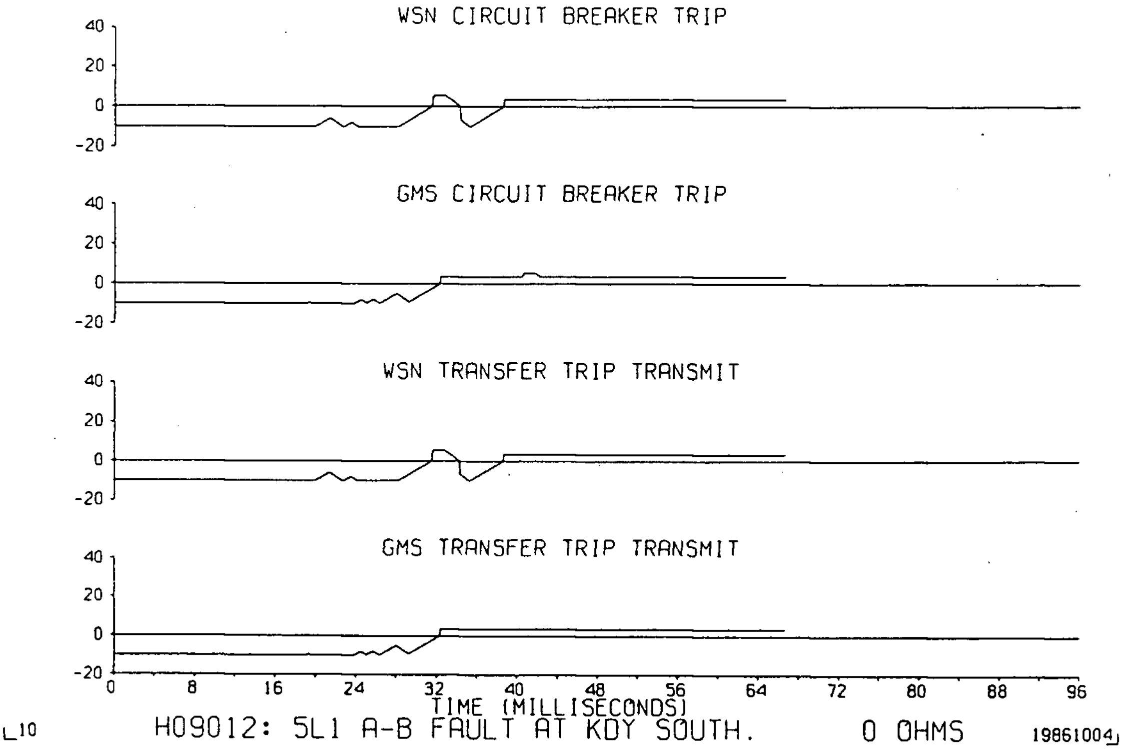

Fig. 15(j). Transfer trip and Williston circuit breaker trip waveforms

Referring to fig. 15(c), both phase- and ground-fault reverse blocking correctly remains low, as do both direct-trip signals. Of the permissive-trip (overreaching) signals, only the phase-fault component responds, due to 21L2 and the supervisory relay 50L.

Referring to fig. 15(d), the combined phase- and ground-fault permissive signal is high due to the phase-fault component. The lack of blocking permits this **combined permissive** signal to raise a **local forward permissive** signal, enabling permissive tripping from the Williston end. The **direct local trip** correctly remains quiescent.

Figure 15(e) shows the waveforms for the G.M. Shrum phase-fault protection. The 21LX Q-switching output has responded 3 ms after the fault. The zone 2 overreaching relay 21L2 picks up briefly 19 ms after the fault and then permanently 7 ms later (on phase coincidence during the next half-cycle).† The distance supervision relay 50L is held high first by load current and later by fault current.

Since the fault is on the opposite (i.e. Williston) side of the Kennedy series capacitor bank, the underreaching distance relay 21L1 would ordinarily be expected to pick up. The bypassing of the series capacitors due to the flashing of the protective gaps has shifted the fault out of zone 1 reach, however, before 21L1 has had time to operate.

Figure 15(f) shows the waveforms for the G.M. Shrum ground-fault protection. All overcurrent relays properly remain quiescent. It is interesting to note that directional element 32F has been picked up by load current (ordinarily it

†The temporary dropout here and in the output of SD-2H relays in other cases was due to an oversight in the modelling of the SD-2H relay—in the actual relay the output is latched for approximately one cycle.

would be muted as was the case with the Williston directional elements).

Figure 15(g) shows the direct-trip, permissive-trip, and reverse blocking waveforms for G.M. Shrum-end protection. Only the **phase-fault permissive** signal becomes high (due to 21L2 pickup and distance supervision 50L).

The combined phase- and ground-fault waveforms for G.M. Shrum are shown in fig. 15(h). The lack of reverse blocking has enabled the **combined-permissive** signal (high due to the **phase-fault permissive** component) to establish a **local forward permissive** condition, enabling permissive tripping from the G.M. Shrum end.

The **permissive-trip transmit** and **repeat-if-no-block** signals are shown in fig. 15(i) for both Williston and G.M. Shrum. Note that the transmission of a permissive-trip signal from Williston has started timing for the G.M. Shrum **repeat-if-no-block** signal. Similarly, G.M. Shrum permissive trip has started Williston **repeat-if-no-block**.

The Williston and G.M. Shrum **transfer-trip transmit** and **circuit breaker trip** signals are shown in fig. 15(j). Since the trip is due to a permissive operation, these waveforms arise from the AND combination of the **permissive-trip transmit** signals, as can be seen by comparison of figs. 15(i) and (j).†

The Williston circuit breaker thus gets a trip command 27 ms after the fault as a result of a permissive-trip operation.

†When making the comparison, the signal from the remote end must be delayed by the 9 ms channel propagation time before being combined with the signal from the local end.

b. Case H09003

Case H09003 is for an internal A-phase SLG fault on the north side of the Kennedy series capacitor bank. The large power system model was used for this simulation. The fault was applied 5.61 ms after the start of the simulation, corresponding to a point-on-wave angle of 143° between the faulted phase and ground. The fault resistance is 250Ω. The duration of this simulation was extended to 105 ms to fully show the operation of the protection.

The protection waveforms are shown in fig. 16(a-j). Apart from the operation of fault-detecting relay 21LX and the current supervision relay 50L, the Williston phase-fault relays remain quiescent, as can be seen from fig. 16(a).

Referring to fig. 16(b), the directional elements 32F/R remain muted until 32F picks up 7 ms after the fault. The low-set blocking element 50LN/IOL picks up 11 ms after the fault, and the 50LN/IOH permissive element picks up 7 ms later. The fault current is too low to cause the direct-tripping 50LN/IOD element to react, and 50LN1S is too slow to be of consequence here.

Since the reverse directional element 32R does not pick up, reverse blocking is inhibited in spite of 50LN/IOL, as can be seen from fig. 16(c). The **ground-fault permissive** signal is enabled by the operation of 50LN/IOH with 32F picked-up.

Referring to fig. 16(d), the **combined permissive** signal, enabled by the ground permissive component, raises a **local forward permissive** condition due to the lack of reverse blocking, thus enabling permissive tripping from the Williston end.

Figure 16(e) shows no activity of the phase-fault protection at G.M. Shrum. For the ground-fault protection shown in fig. 16(f), directional

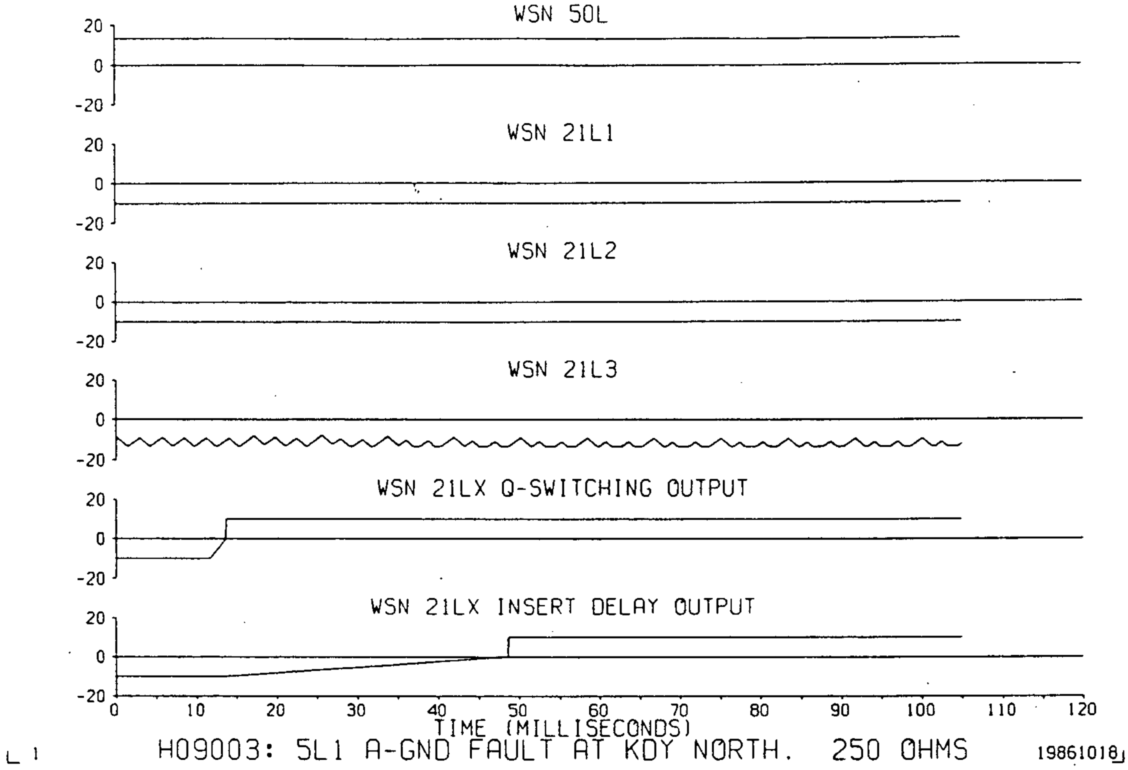

Fig. 16(a). Williston phase-fault protection waveforms

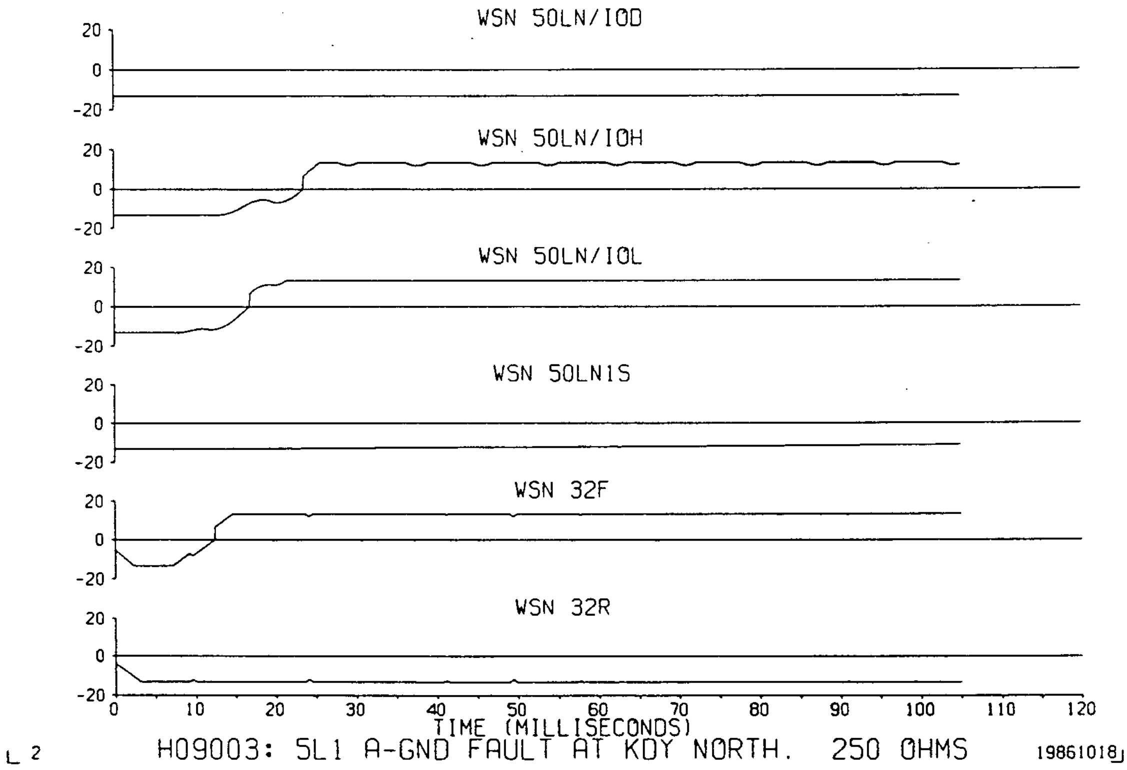

Fig. 16(b). Williston ground-fault protection waveforms

Fig. 16. Protection waveforms for case H09003

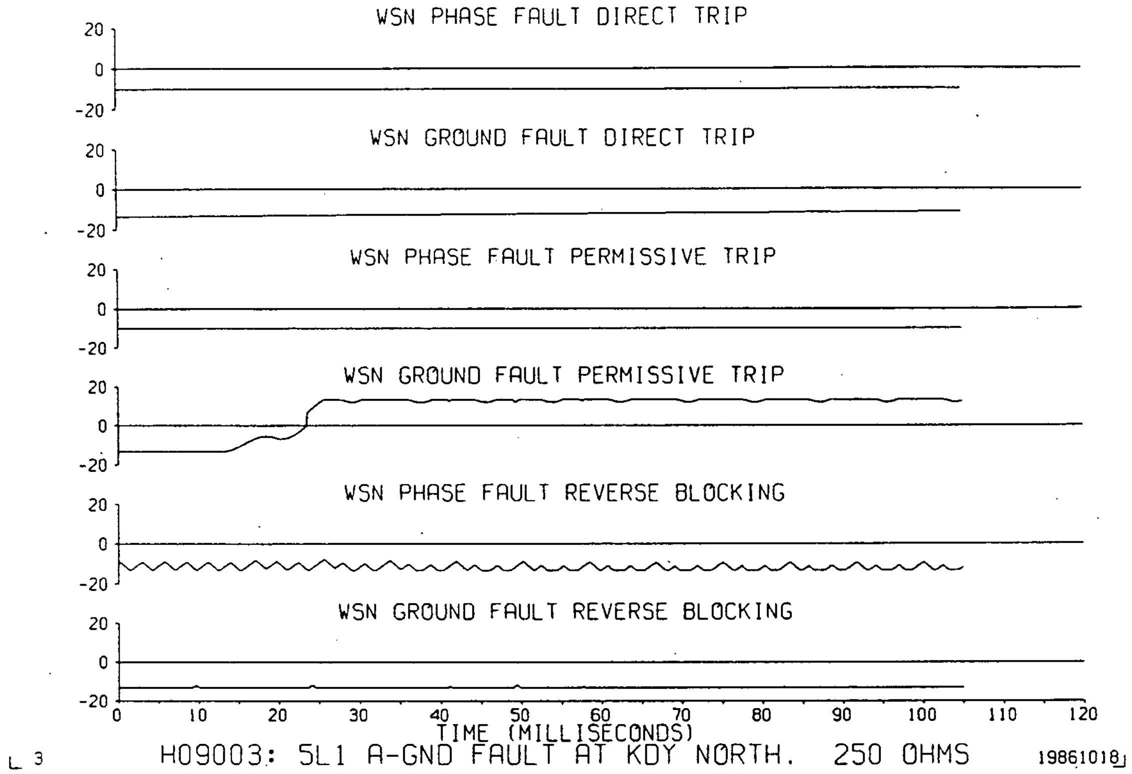

Fig. 16(c). Williston phase- and ground-fault direct, permissive, and blocking signals

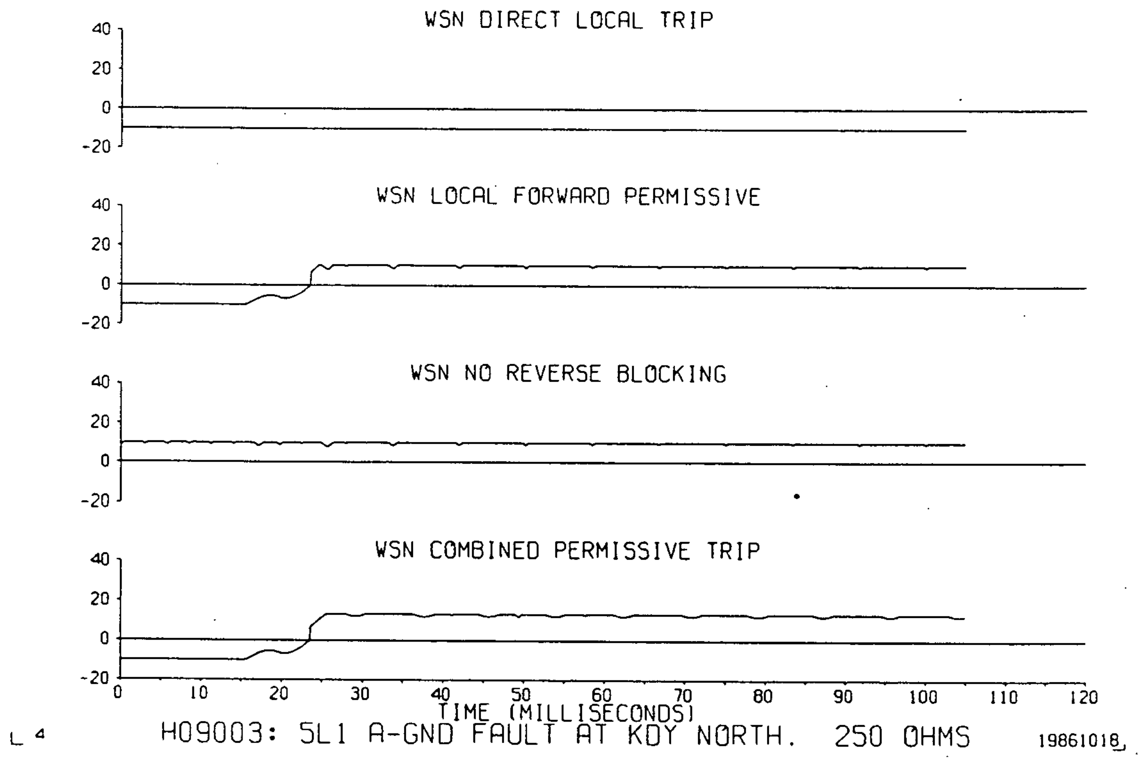

Fig. 16(d). Williston local reverse blocking and direct- and permissive-trip signals

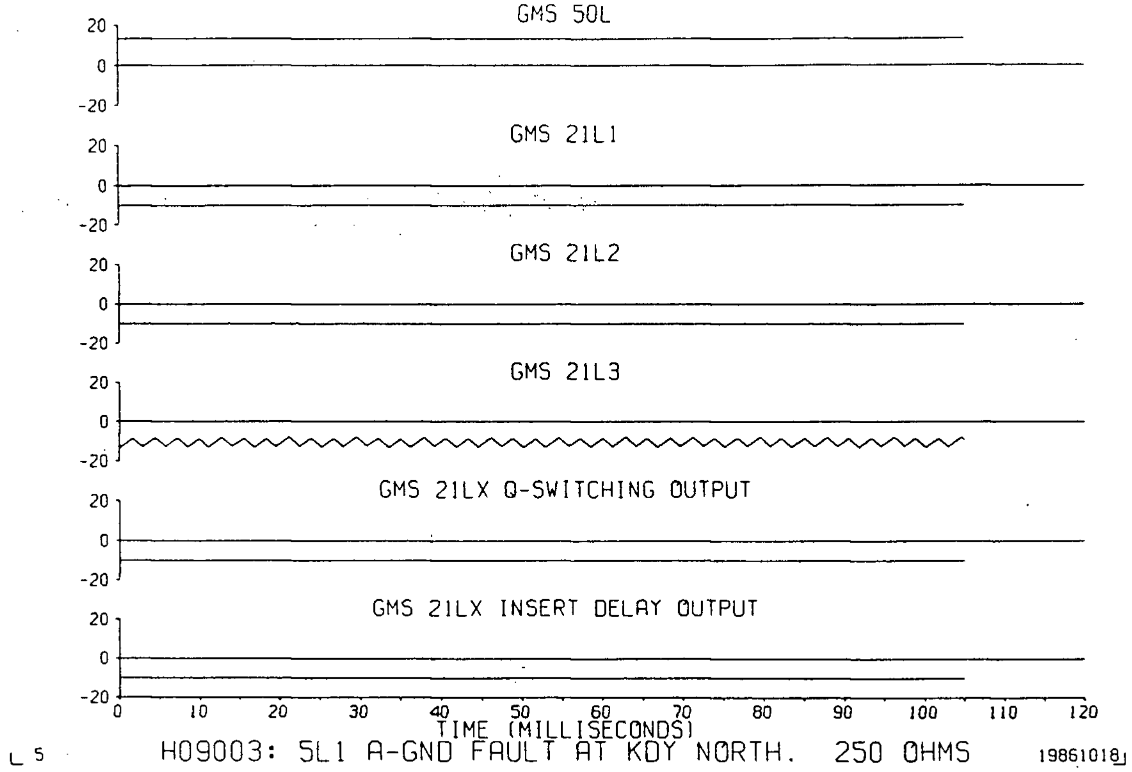

Fig. 16(e). G.M. Shrum phase-fault protection waveforms

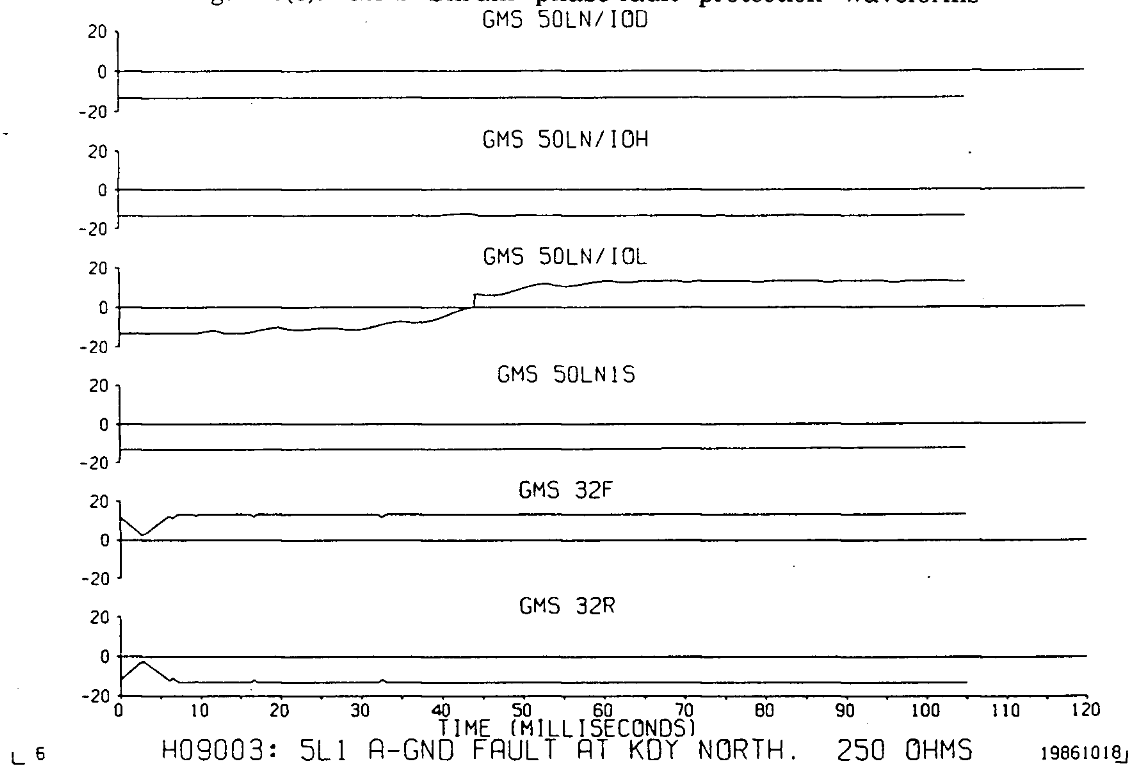

Fig. 16(f). G.M. Shrum ground-fault protection waveforms

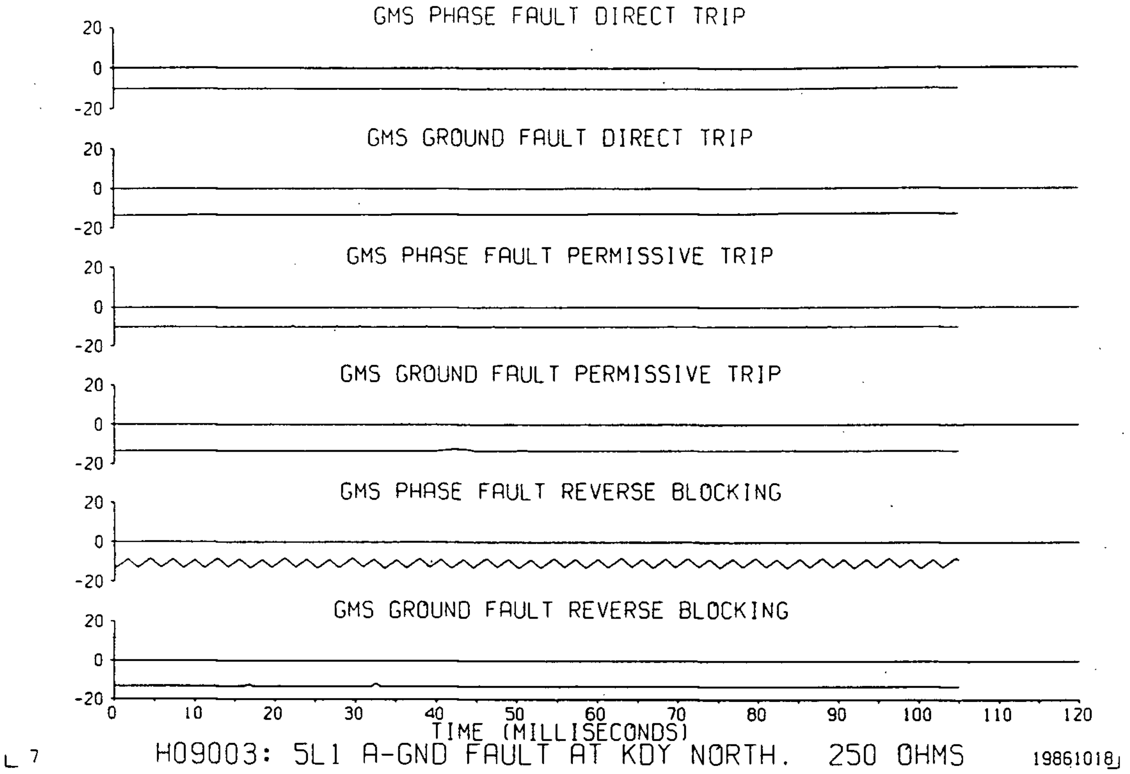

Fig. 16(g). G.M. Shrum phase- and ground-fault direct, permissive, and blocking signals

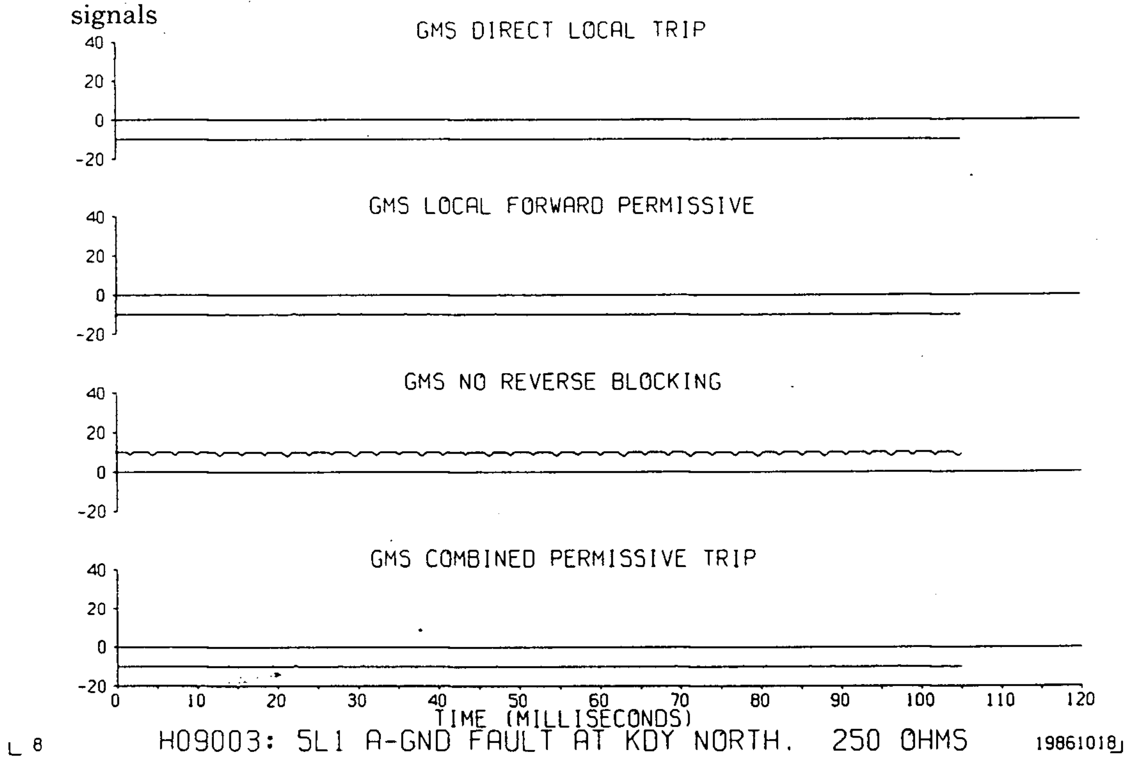

Fig. 16(h). G.M. Shrum local reverse blocking and direct- and permissive-trip signals

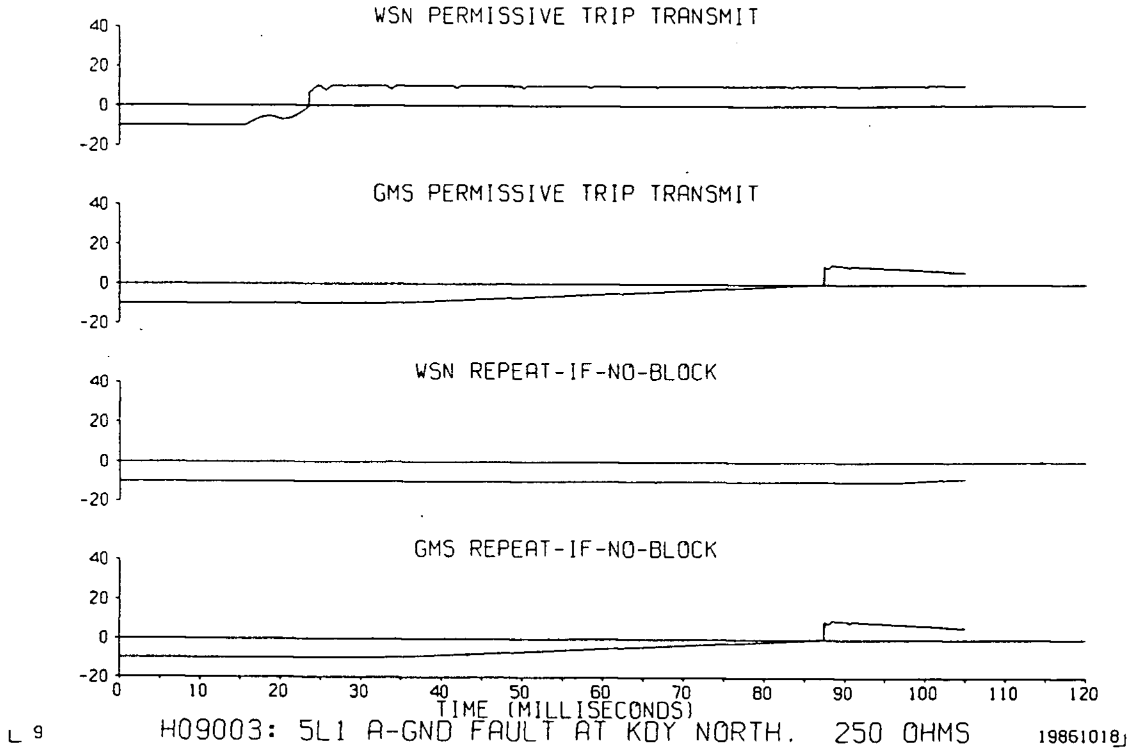

Fig. 16(i). Permissive trip and repeat-if-no-block waveforms

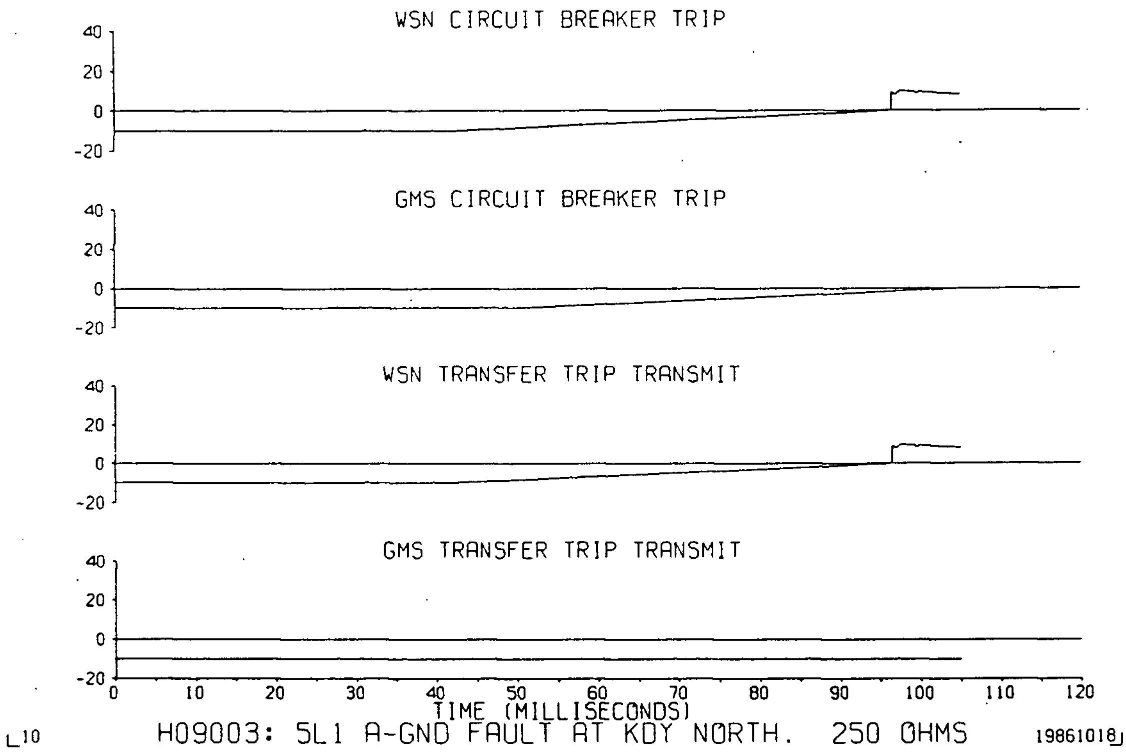

Fig. 16(j). Transfer trip and Williston circuit breaker trip waveforms

element 32F is initially high due to load current. Only the low-set blocking element 50LN/IOL picks up, 39 ms after the fault. Since the reverse directional element is low, however, no reverse blocking will result, as can be seen from fig. 16(g).

It is also clear from this and the following figure that none of the G.M. Shrum elements have detected the fault. Ordinarily this would mean that the fault would have to be cleared by the secondary ground-overcurrent relay 50LN1S, which is very slow to operate for this level of current. The **repeat-if-no-block** feature, however, allows the Williston **permissive-trip transmit** signal to cause a trip after being repeated from the G.M. Shrum end, as can be seen in fig. 16(i). Thus the breaker is tripped locally at Williston, with a transfer-trip to G.M. Shrum, 91 ms after the fault. This shows the advantage of the **repeat-if-no-block** feature.

c. Case H10006

Case H10006 is for an external AC phase-to-phase fault on the Williston bus, immediately behind the Williston-end protection. The reduced power-system model was used for this simulation. The fault was applied at 7.04 ms, corresponding to a point-on-wave angle of 143° between the faulted-phase voltages. Fault resistance is ignored.

The protection waveforms are shown in fig. 17(a-j). The Williston fault-detecting relay 21LX responds with a high Q-switching control signal within 2 ms of the fault, as can be seen from fig. 17(a). The reverse blocking distance relay 21L3 picks up temporarily 10 ms after the fault, and permanently 8 ms later on the next half-cycle phase coincidence. The distance supervision

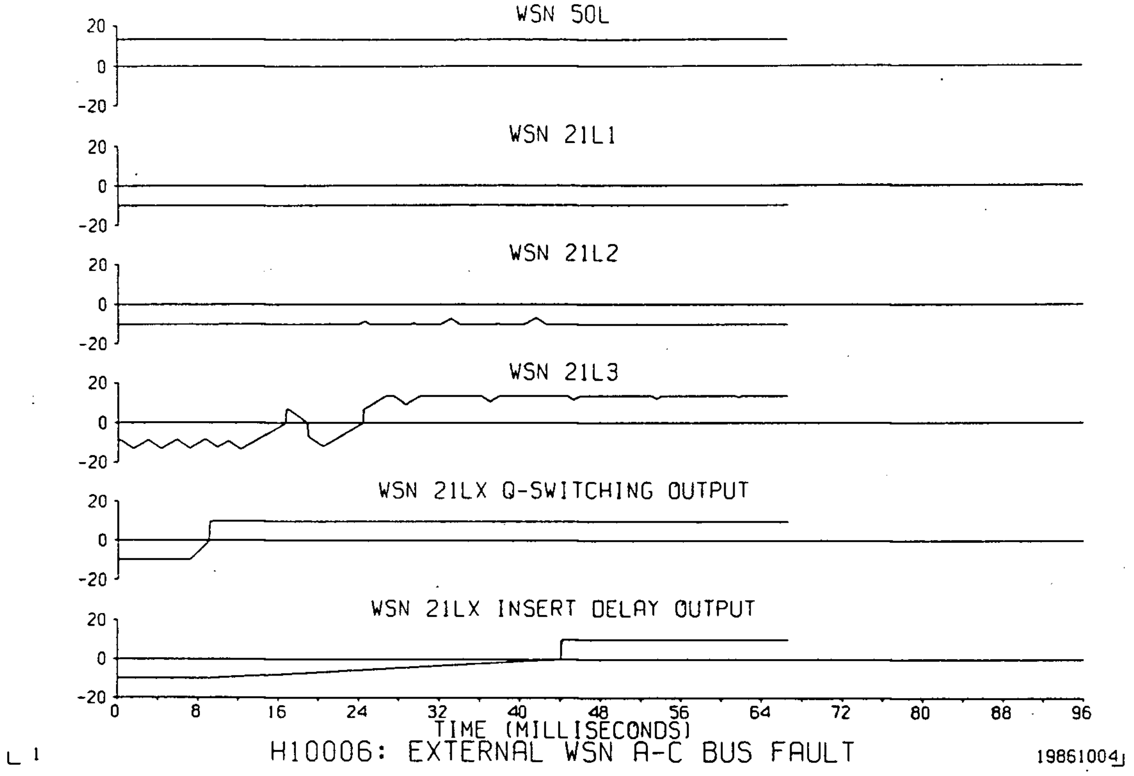

Fig. 17(a). Williston phase-fault protection waveforms

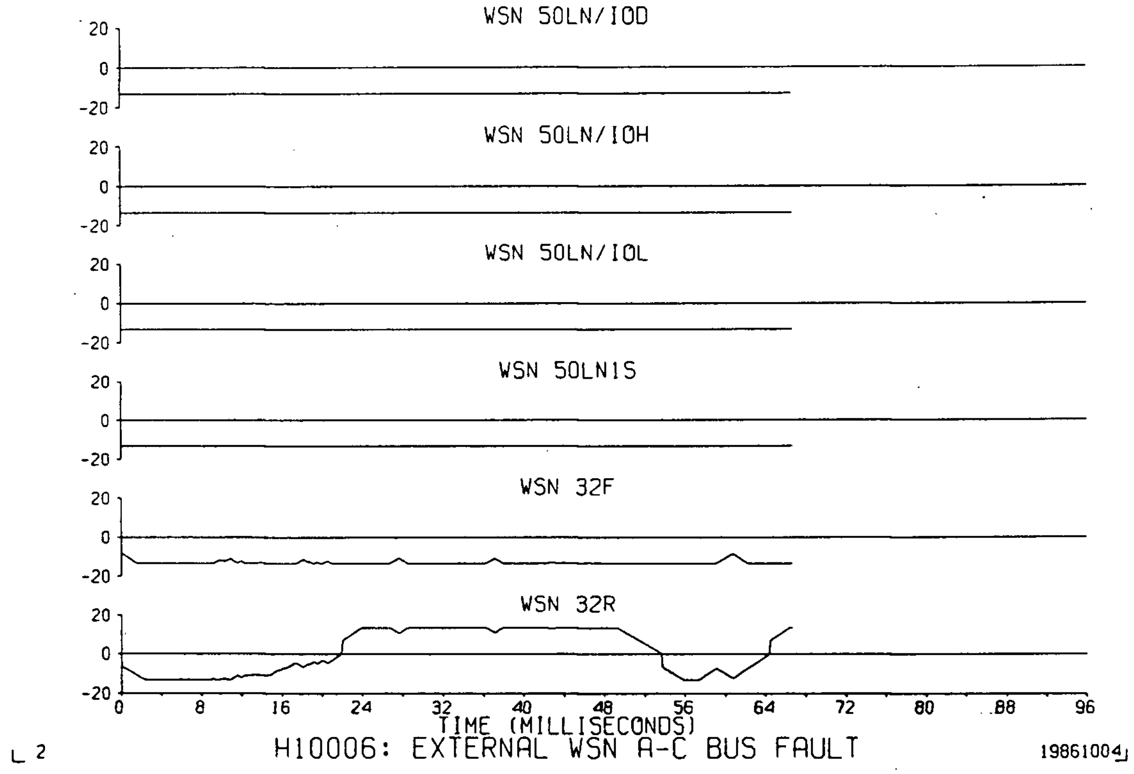

Fig. 17(b). Williston ground-fault protection waveforms

Fig. 17. Protection waveforms for case H10006

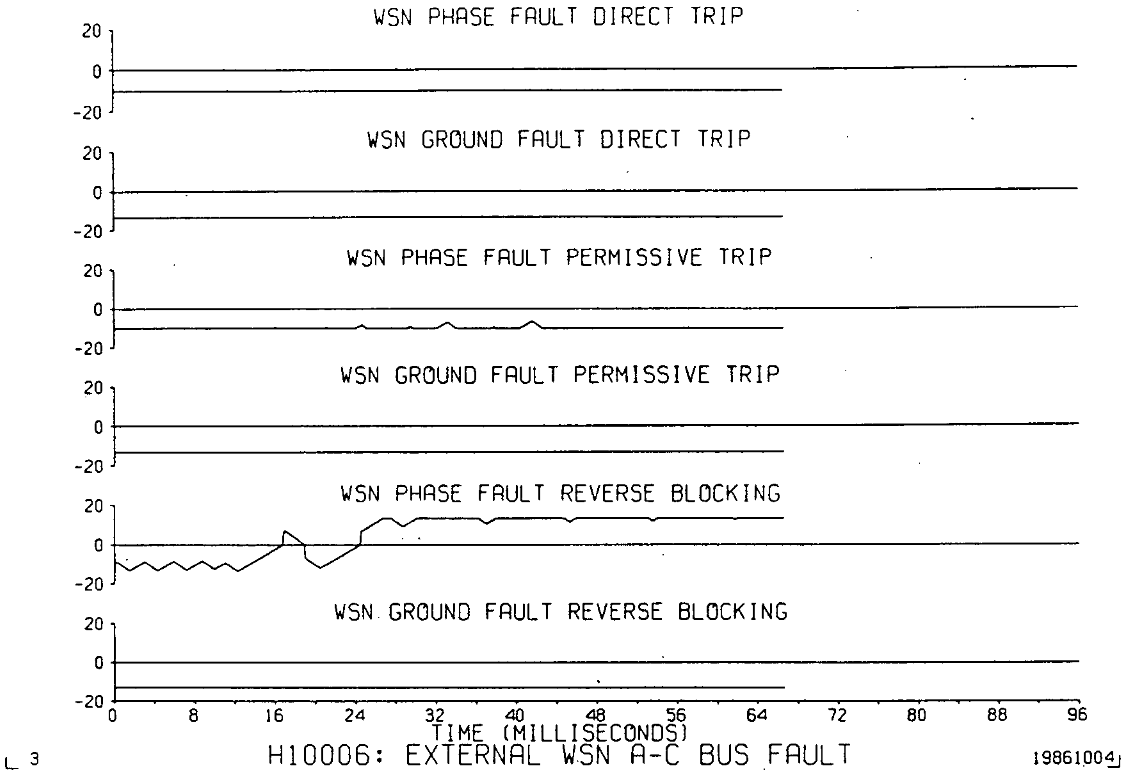

Fig. 17(c). Williston phase- and ground-fault direct, permissive, and blocking signals

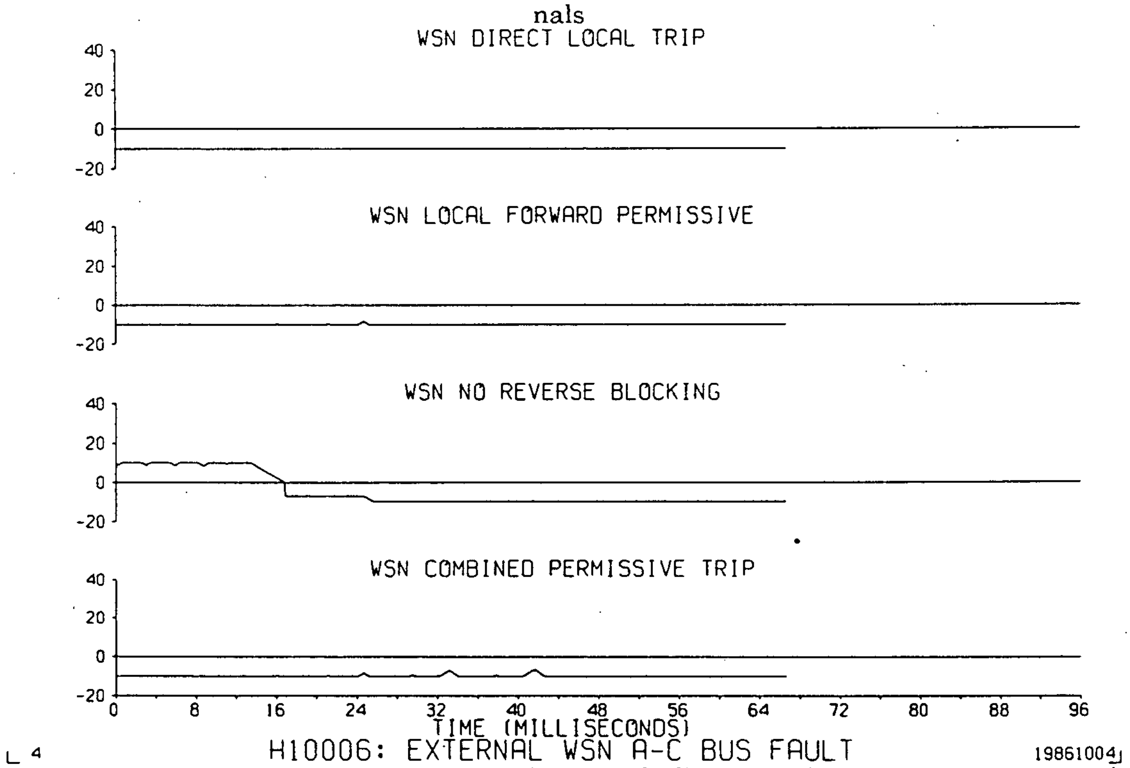

Fig. 17(d). Williston local reverse blocking and direct- and permissive-trip signals

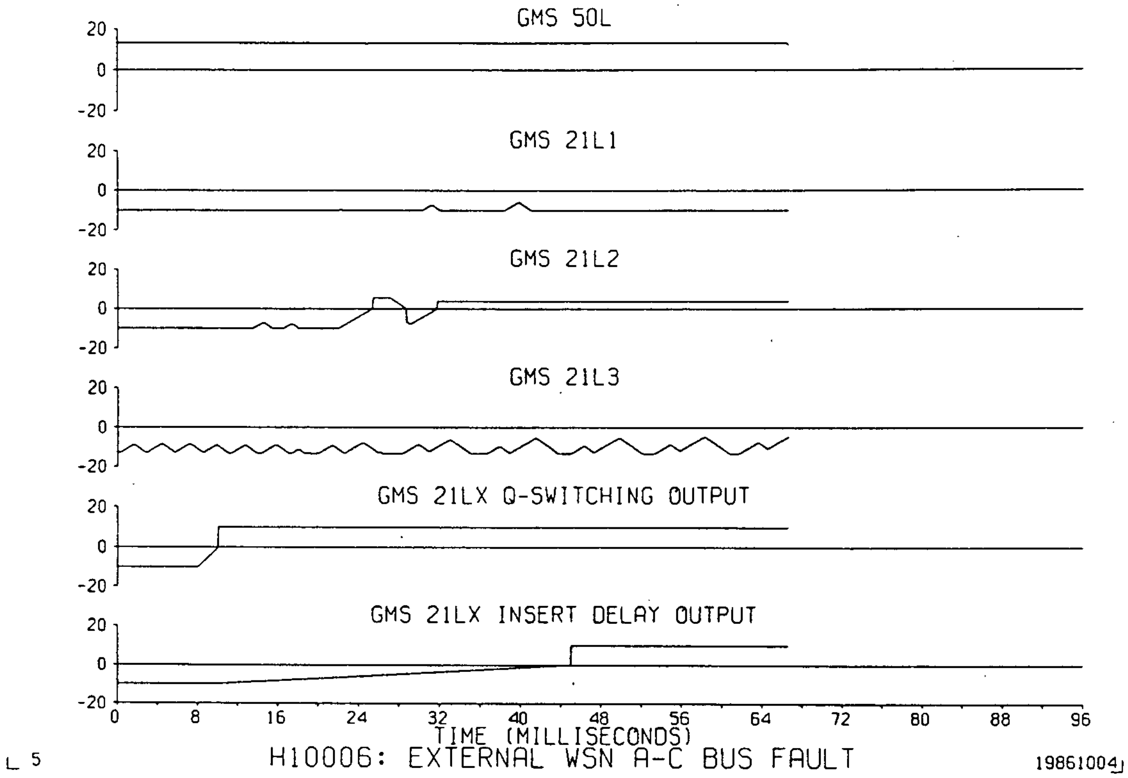

Fig. 17(e). G.M. Shrum phase-fault protection waveforms

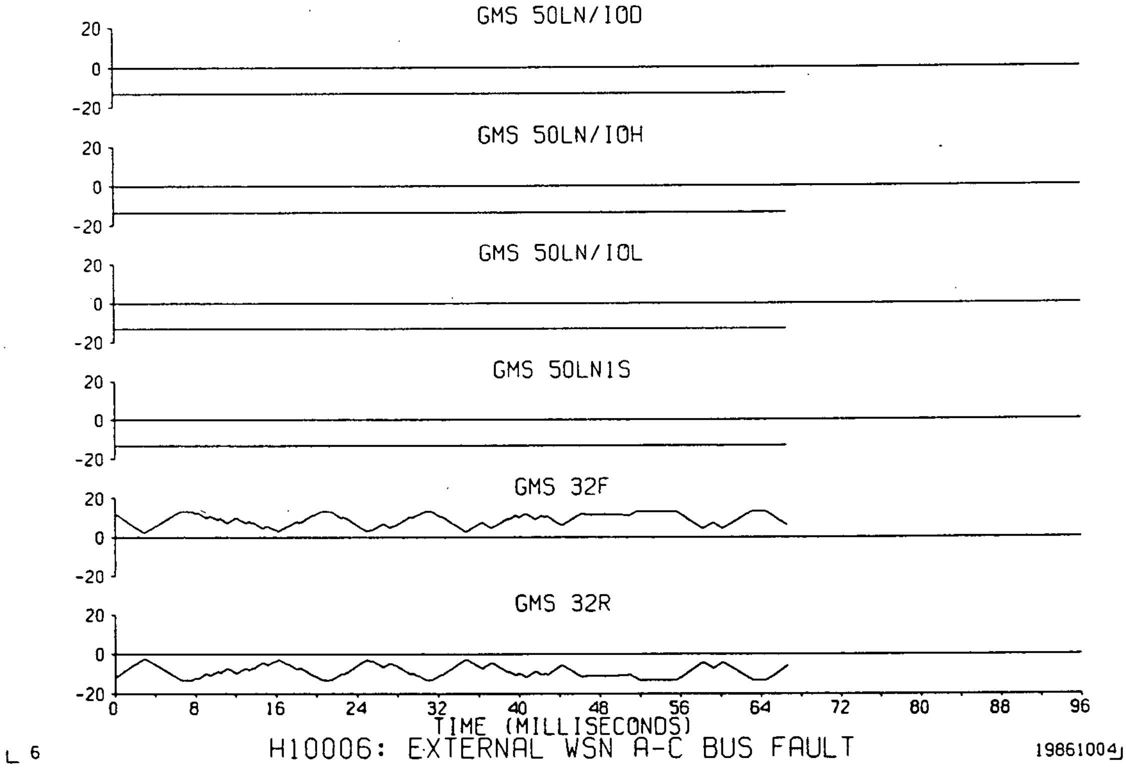

Fig. 17(f). G.M. Shrum ground-fault protection waveforms

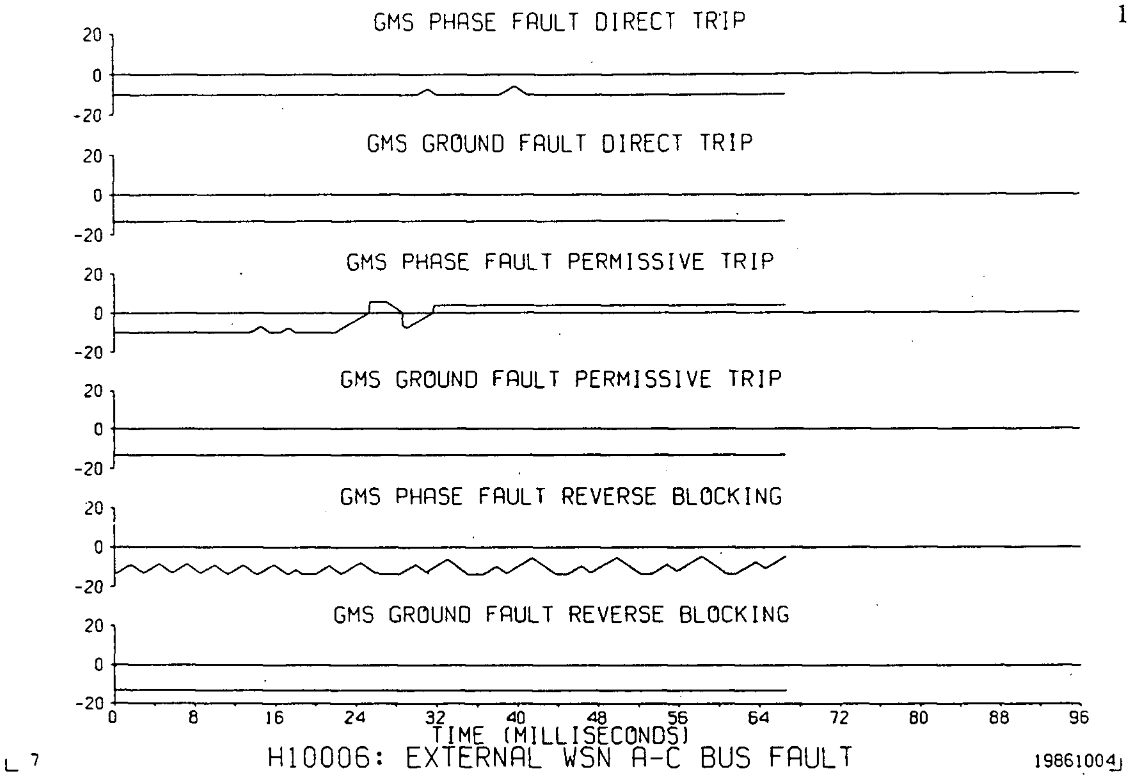

Fig. 17(g). G.M. Shrum phase- and ground-fault direct, permissive, and blocking signals

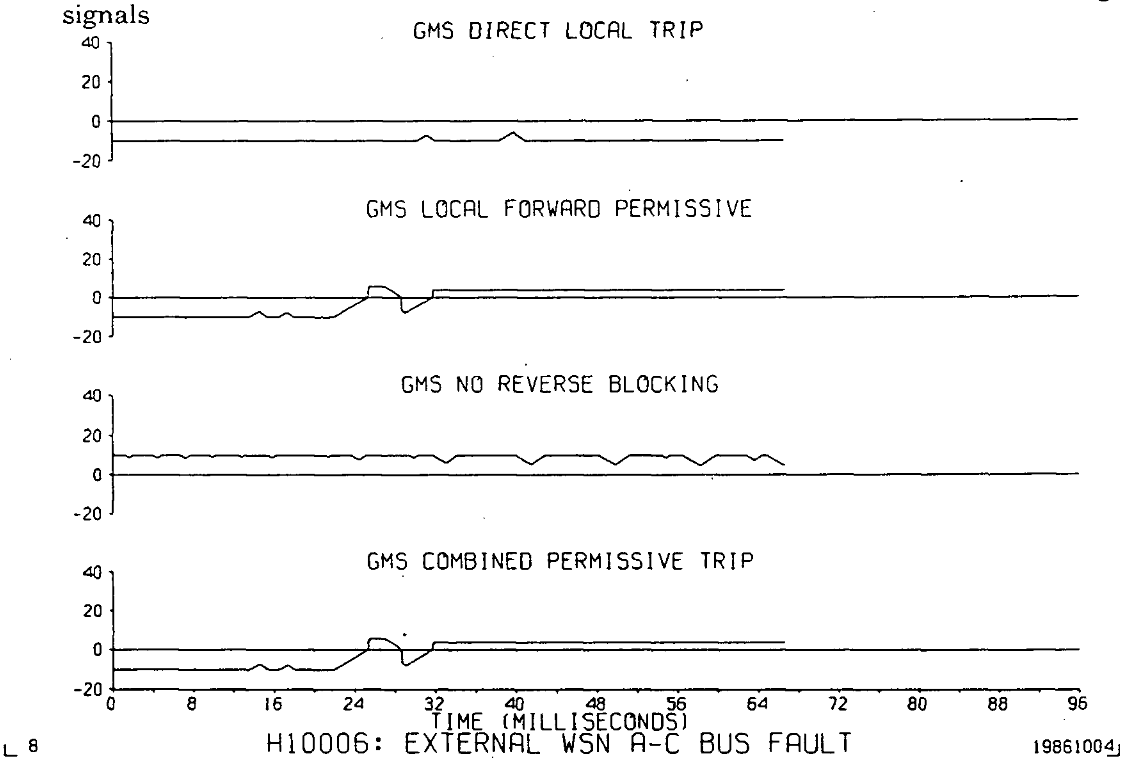

Fig. 17(h). G.M. Shrum local reverse blocking and direct- and permissive-trip signals

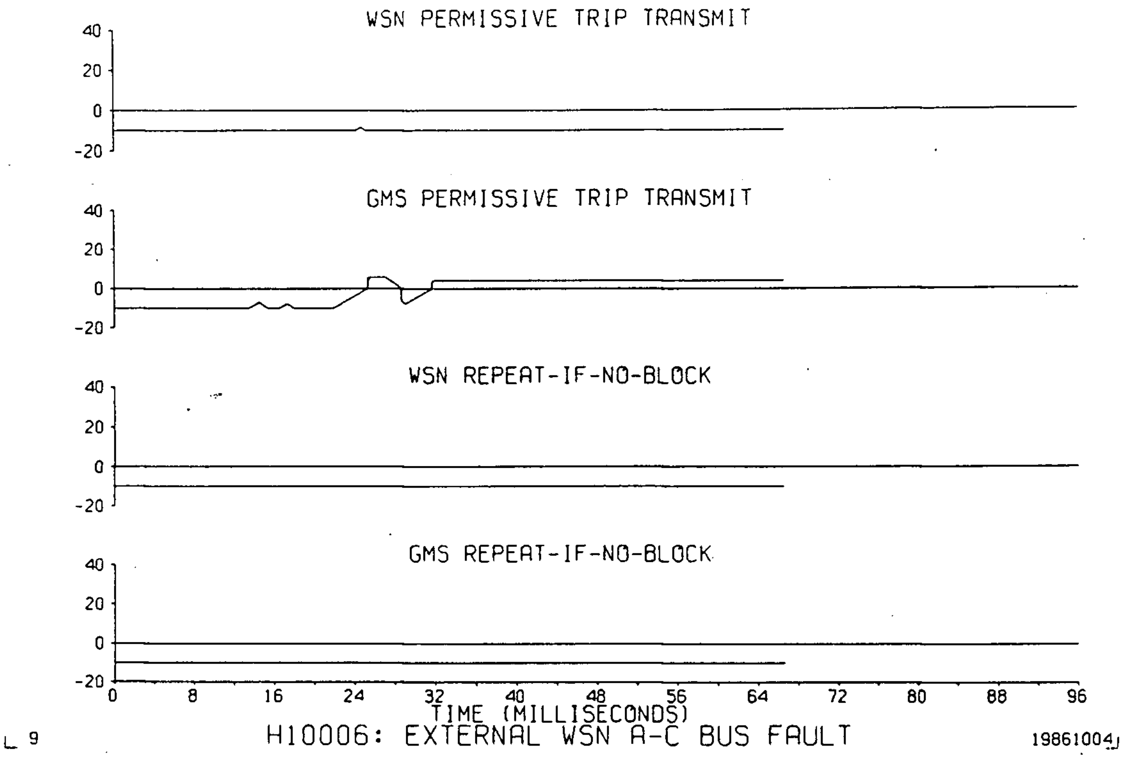

Fig. 17(i). Permissive trip and repeat-if-no-block waveforms

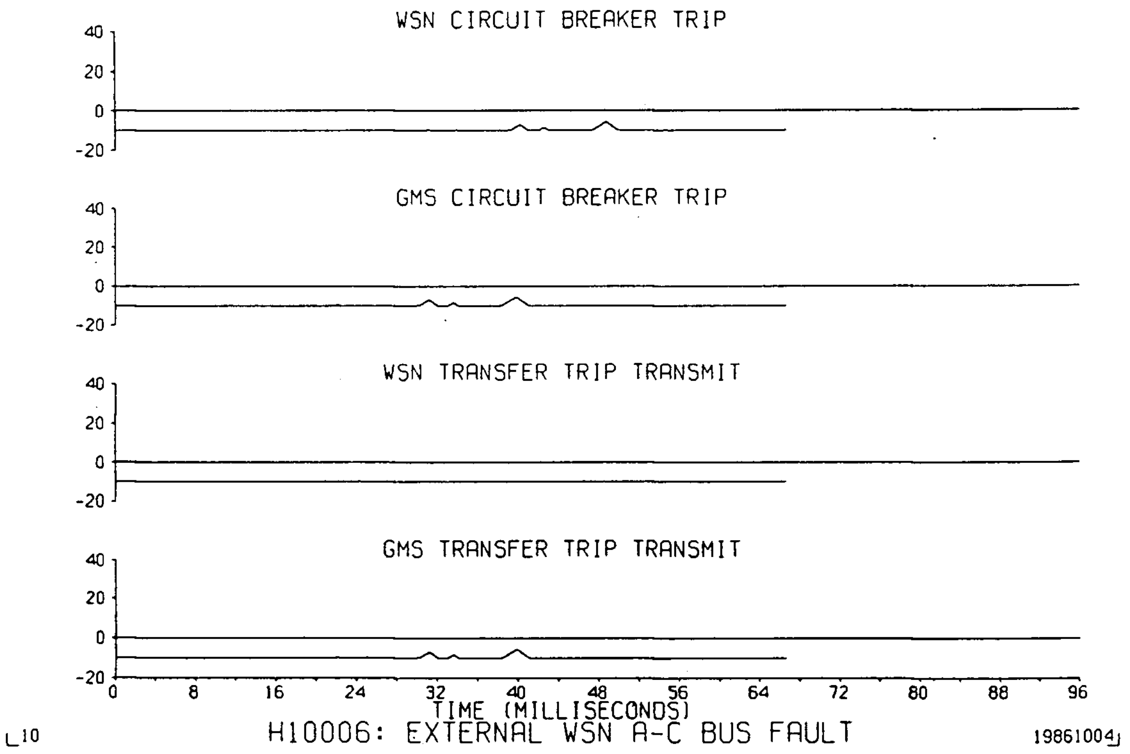

Fig. 17(j). Transfer trip and Williston circuit breaker trip waveforms

relay 50L is high throughout. Note that there is a slight tendency for 21L2 to operate on transients until the **insert-delay** control signal from the 21LX causes the insertion of a pickup delay.

All ground-fault relays remain quiescent, as can be seen from fig. 17(b).

The combination of 50L and 21L3 high produce a **phase-fault reverse blocking** condition, shown in fig. 17(c). This causes the **no reverse blocking** signal in fig. 17(d) to drop low and hold. (Note that the 100 ms blocking memory prevents the temporary dropout of the **phase-fault reverse blocking** from causing the **no reverse blocking** signal to reset high.)

The G.M. Shrum fault-detecting relay 21LX produces a high Q-switching control signal 3 ms after the fault, as can be seen in fig. 17(e). The overreaching distance element 21L2 picks up temporarily 18 ms after the fault and permanently 7 ms later.

Note the slight residual tendency of 21L1 to overreach on the series capacitor transient. NLR makes this tendency clearly visible, showing that it is too little to be of concern. The overreaching tendency could be investigated for other fault conditions (point-on-wave angle, etc.); the relative effect of each condition could be easily seen from the relative levels of the 21L1 response. Without NLR, this kind of comparison would require the evaluation of several internal signals from each of the three phase elements of 21L1. The task can become unmanageable. The reader is referred to the statements by Muller quoted on page 20.

The G.M. Shrum ground-fault protection remains quiescent, as can be seen from fig. 17(f). Note the effect of the high-frequency transients on the response of 32F/R, producing the characteristic dithering behaviour of the block-average phase comparator. (Recall that the actual directional elements use a block-instantaneous comparator, which will exhibit a repetitive resetting behaviour under these conditions.) The dithering could have been further reduced by using higher-Q input filters. Dithering is more pronounced with the truncated system model than with the full system model, due to the accentuated reflection transients.

Figure 17(g) shows the **phase-fault permissive** signal which has been enabled by the combination of 21L2 and the 50L distance supervision. The misoperation tendency of 21L1 is also visible, in the **phase-fault direct trip** signal. It is this ability of NLR to propagate problem indicators through the scheme logic which makes it so powerful. Only a few of the final signals need be monitored to detect a potential problem, thus permitting a "wide angle" view of protection operation without missing critical details. Where a potential problem is identified, it can be traced back up the logic path in subsequent simulations, "zooming in" on the problem area. This permits a maximum of information to be gleaned from a minimum of waveforms, while reducing user-interpretation to a reliable minimum. Only with the use of NLR is this possible.

The **phase-fault permissive** signal enables the **combined permissive** signal, which together with the **no reverse blocking** establishes a **local forward permissive** condition, enabling permissive tripping from the G.M. Shrum end. All of this is visible in fig. 17(h).

The resulting tripping signals are visible in figures 17(i) and (j). A permissive-trip signal is transmitted from G.M. Shrum. No corresponding permissive-trip condition exists at Williston, however, so no trip condition results. Note also that the blocking at Williston inhibits the **repeat-if-no-block** feature there.

The G.M. Shrum **transfer-trip transmit**, and thence the Williston **circuit breaker trip** signal, still shows the overreaching tendency of 21L1. (The overreaching tendency, incidentally, is controlled by the "IZ-V" input filter in the SD-2H unit, which has been switched into a high-Q state by the operation of 21LX). NLR has permitted the overreaching tendency to be carried through to the final, circuit-breaker trip signal. NLR clearly shows that whatever risk there is to protection security for this fault condition derives from the 21L1 overreaching tendency.

It is worth noting at this point that NLR is especially valuable for establishing protection security, which is critical to the stability of power system operation and continuity of supply. Horowitz, in a Special Report for CIGRE Group 34 (1980), stated:

> *The balance between dependability . . . and security . . . has always been biased towards tripping. This is now seriously being called into review and slower tripping (although less false trip* [sic]*) may be on the horizon.*

d. Case H09002

Case H09002 is for an external A-phase SLG fault at the Williston end of 5L2. The full power system model was used for this simulation. The simulation was continued through to clearing of the fault. The protection operating times for 5L2 were determined from the simulation of an identical fault on 5L1, using the 5L1 protection model. An omission was subsequently discovered in the protection model, which produced optimistically-fast operation. This was corrected for H09002 but the clearing times for 5L2 were not adjusted. Hence 5L2 clearing is unrealistically prompt. The times used were 26.3 ms to Williston breaker opening after fault initiation, with a 10 ms transfer trip time to G.M. Shrum. The fault was applied at 5.64 ms after the start of simulation.

The protection waveforms are shown in fig. 18(a-j). Inspection of fig. 18(a) shows Williston 21LX pickup some 2 ms after the fault. A very small tendency to mis-operate is shown by 21L2.

Figure 18(b) shows the Williston ground-fault protection waveforms. Note that directional element 32R correctly picks up after fault inception and holds until the fault is cleared by the Williston-end 5L2 breaker. Low-set relay 50LN/IOL picks up shortly after the fault (as 50LN/IOH very nearly does also). After the fault is cleared from the Williston end, ground-permissive relay 50LN/IOH picks up and holds until the fault is cleared at the G.M. Shrum end as well.

The combination of 32R and 50LN/IOL activates a **ground-fault reverse blocking** signal during the time the fault is fed via Williston. The reversal of apparent fault direction (which occurs on clearing from Williston end) causes the combination of 32F and 50LN/IOH to activate a ground-permissive signal until the fault is finally cleared from G.M. Shrum. This is all visible in fig. 18(c).

The ground-permissive signal produces a **combined-permissive** signal, as can be seen in fig. 18(d). Were it not for the blocking memory, this signal would produce a **local forward permissive** condition at Williston which would overlap with the G.M. Shrum **local forward permissive** condition shown in fig. 18(h), causing an incorrect permissive-trip operation. As it is, however, the **ground-fault reverse blocking** condition is maintained well past the apparent

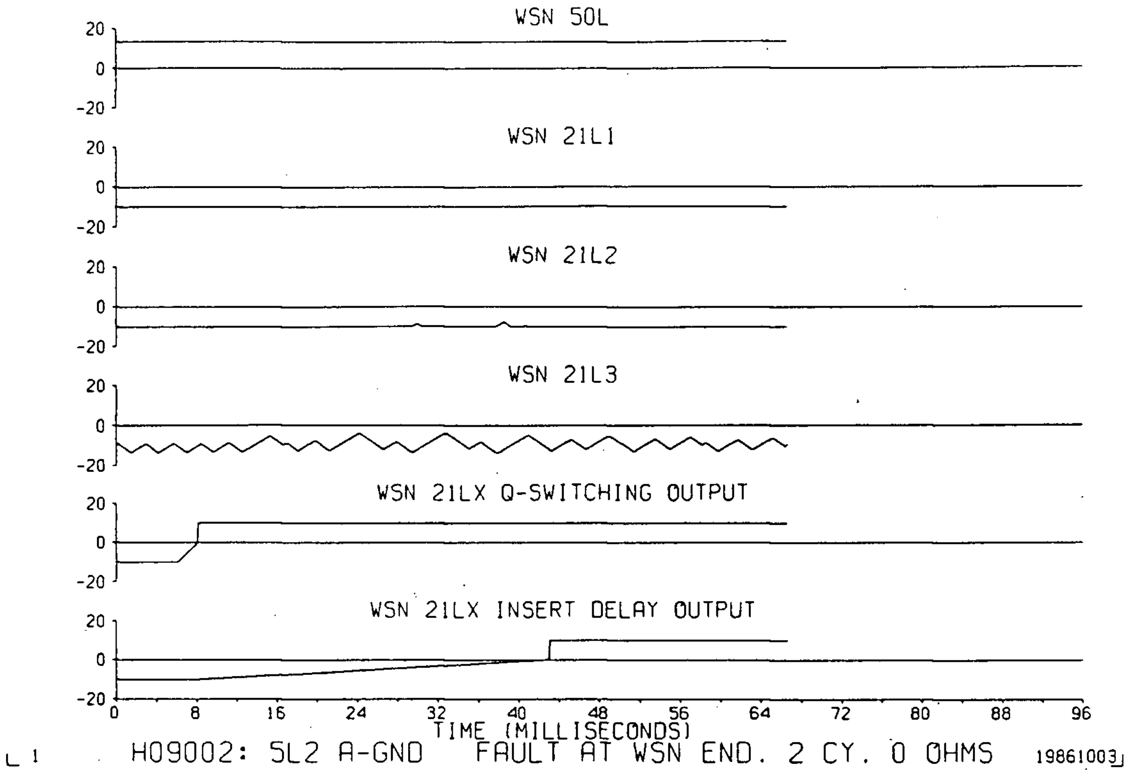

Fig. 18(a). Williston phase-fault protection waveforms

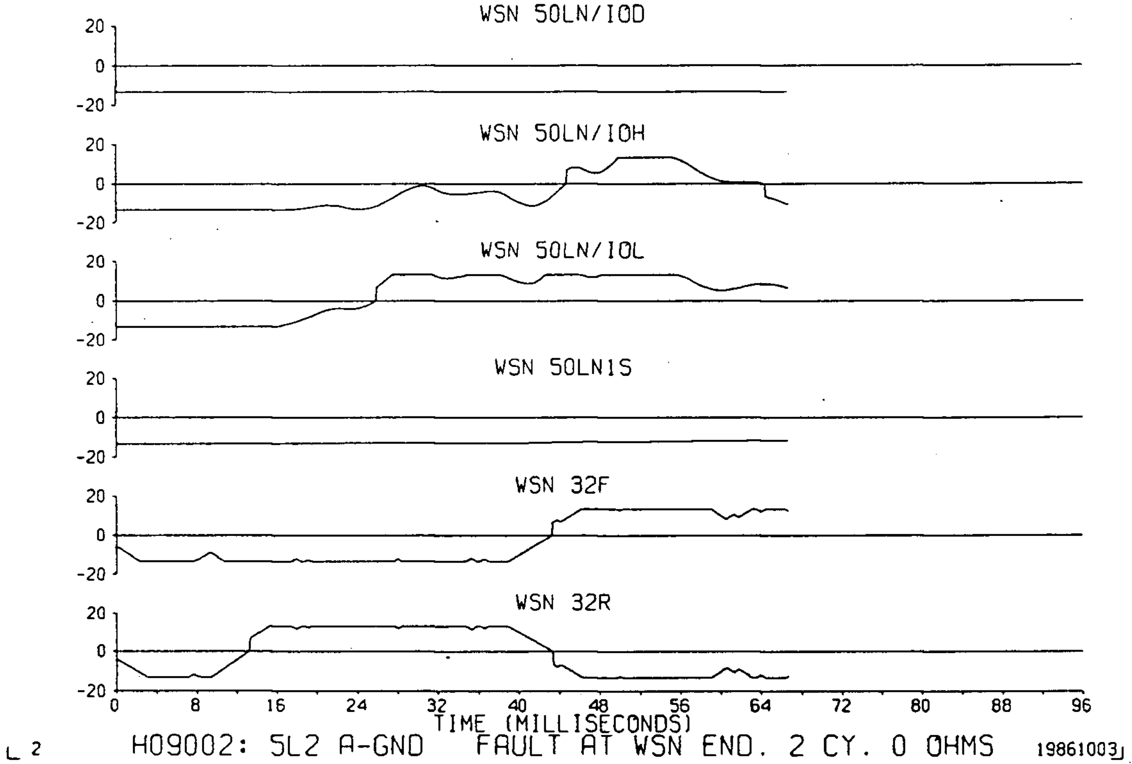

Fig. 18(b). Williston ground-fault protection waveforms

Fig. 18. Protection waveforms for case H09002

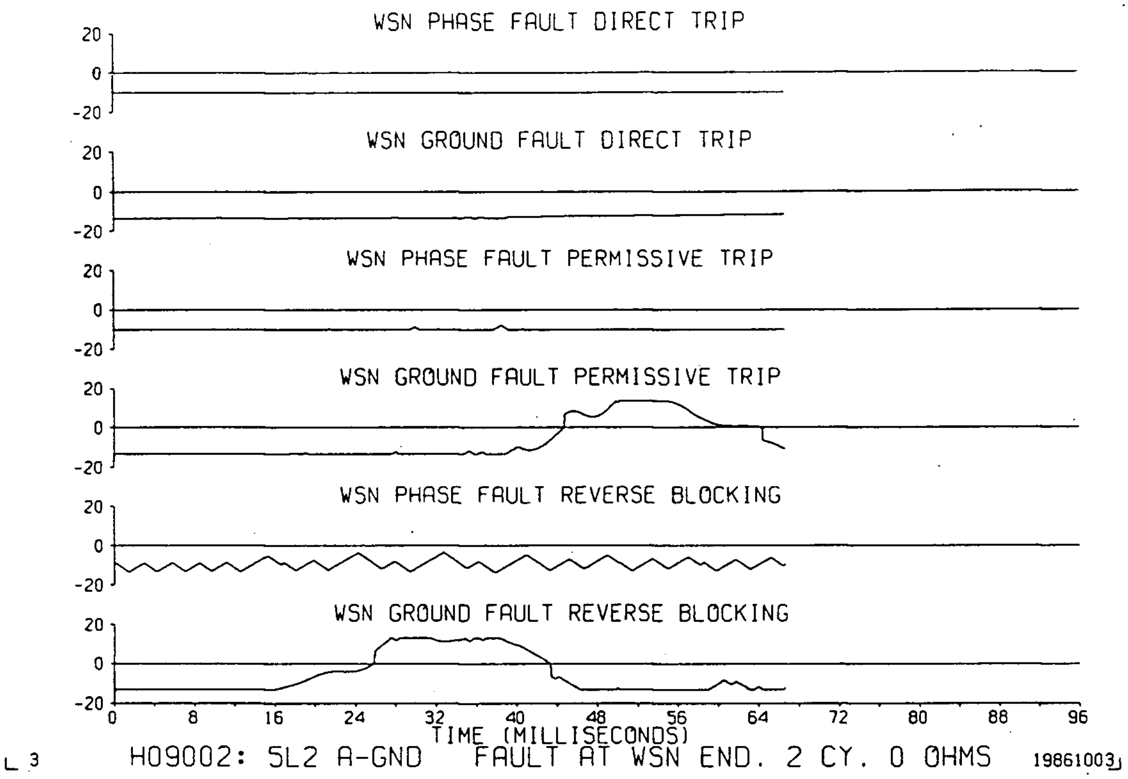

Fig. 18(c). Williston phase- and ground-fault direct, permissive, and blocking signals

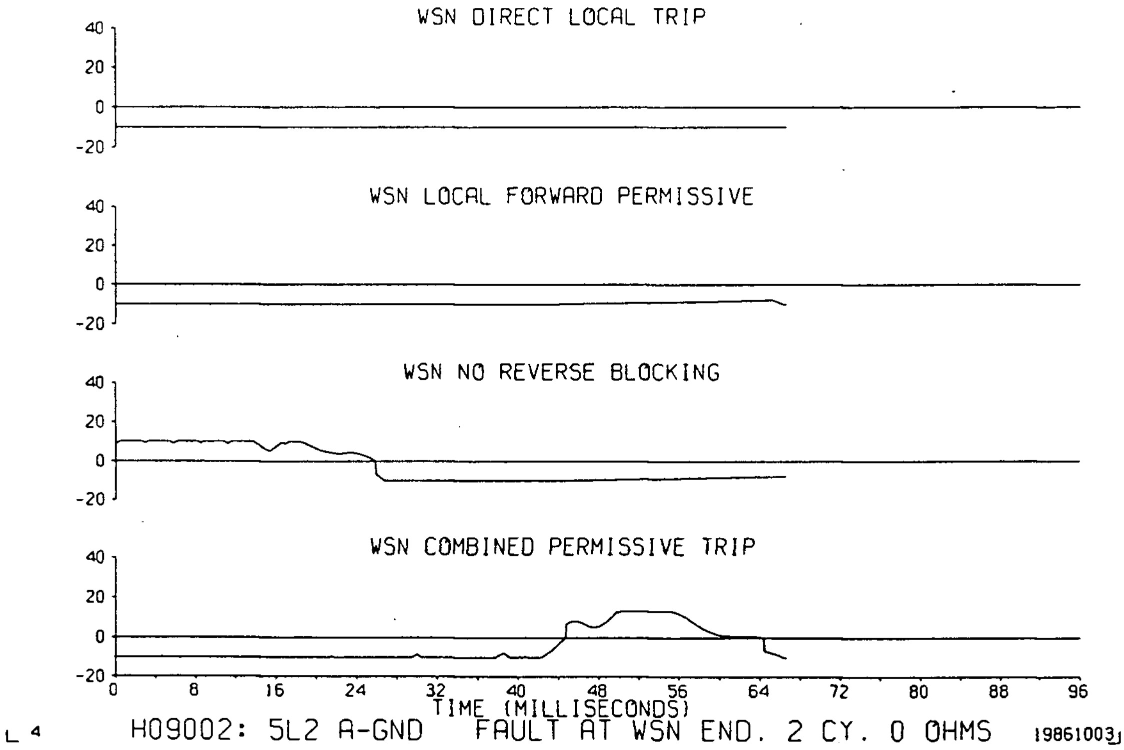

Fig. 18(d). Williston local reverse blocking and direct- and permissive-trip signals

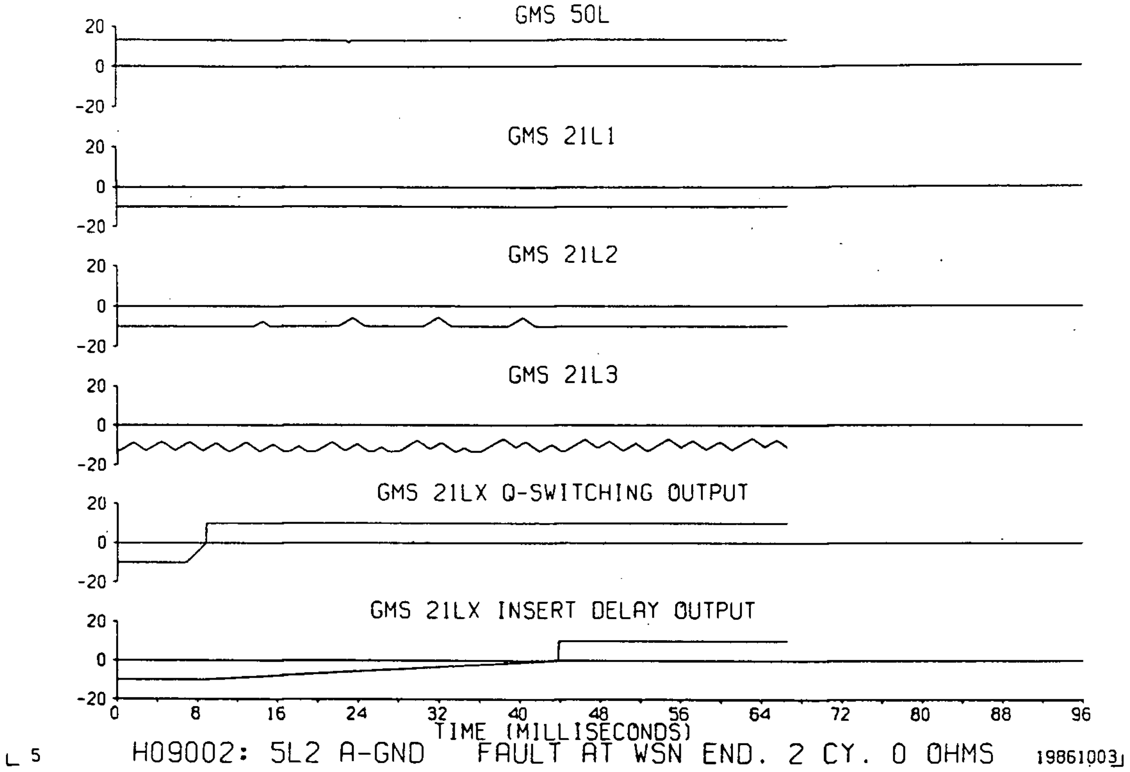

Fig. 18(e). G.M. Shrum phase-fault protection waveforms

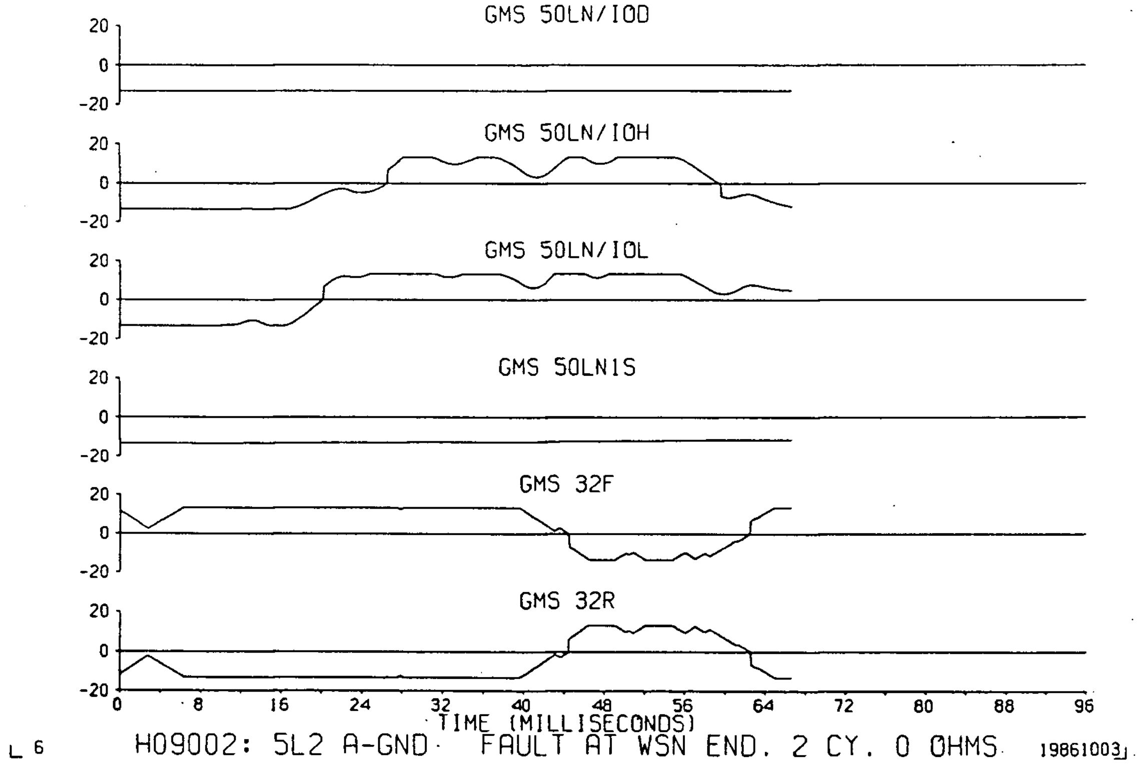

Fig. 18(f). G.M. Shrum ground-fault protection waveforms

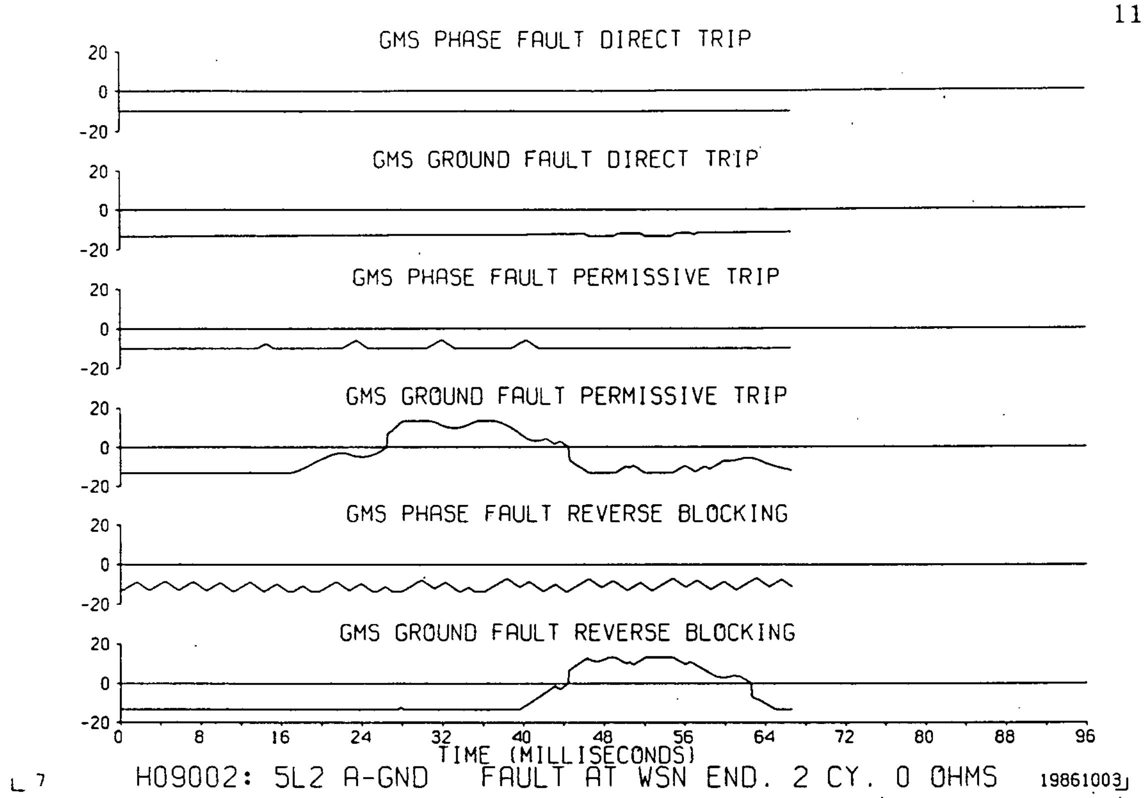

Fig. 18(g). G.M. Shrum phase- and ground-fault direct, permissive, and blocking signals

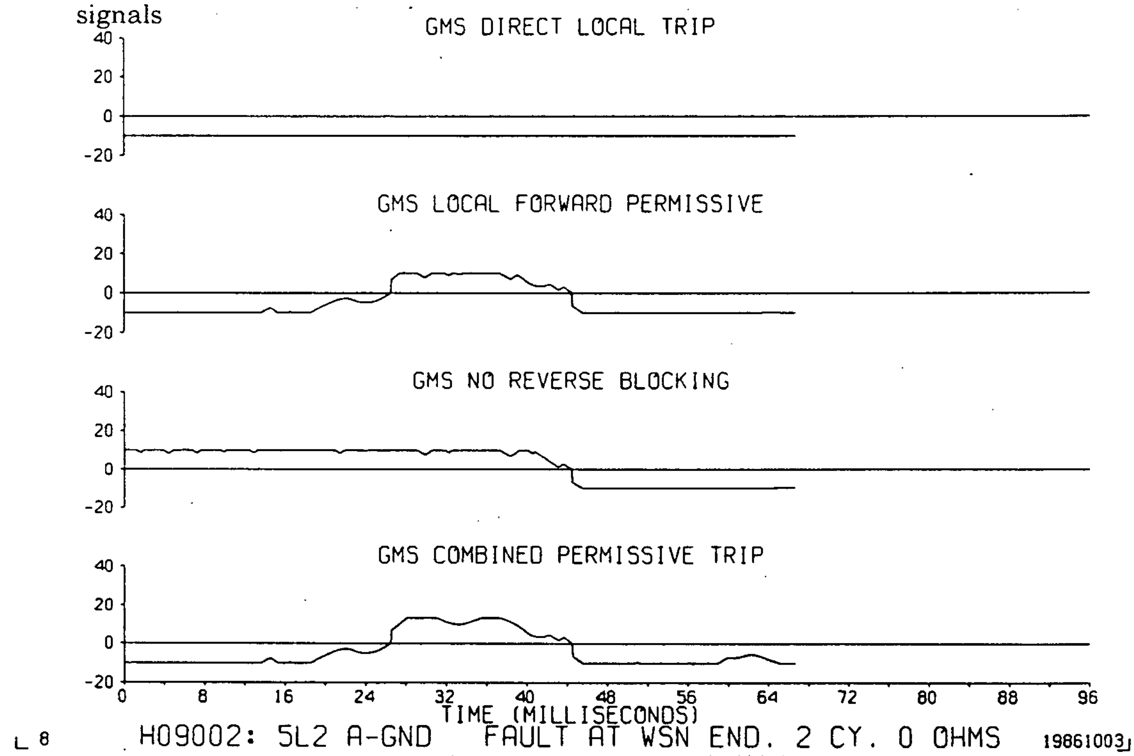

Fig. 18(h). G.M. Shrum local reverse blocking and direct- and permissive-trip signals

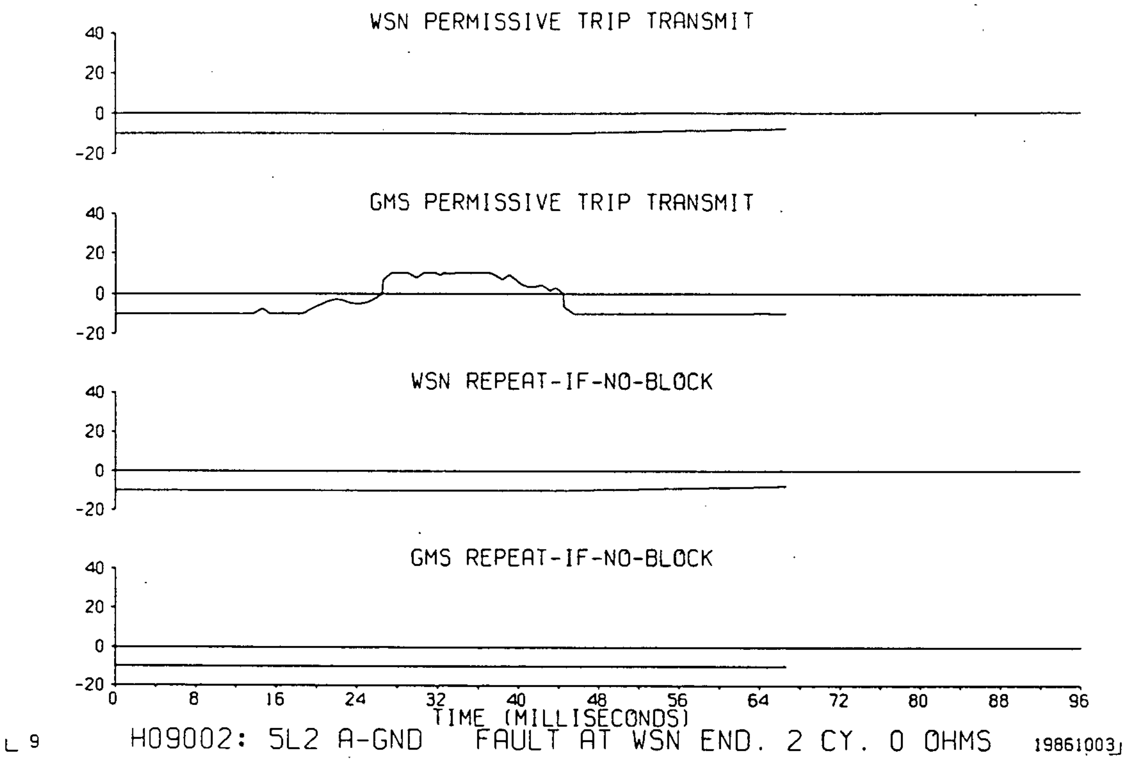

Fig. 18(i). Permissive trip and repeat-if-no-block waveforms

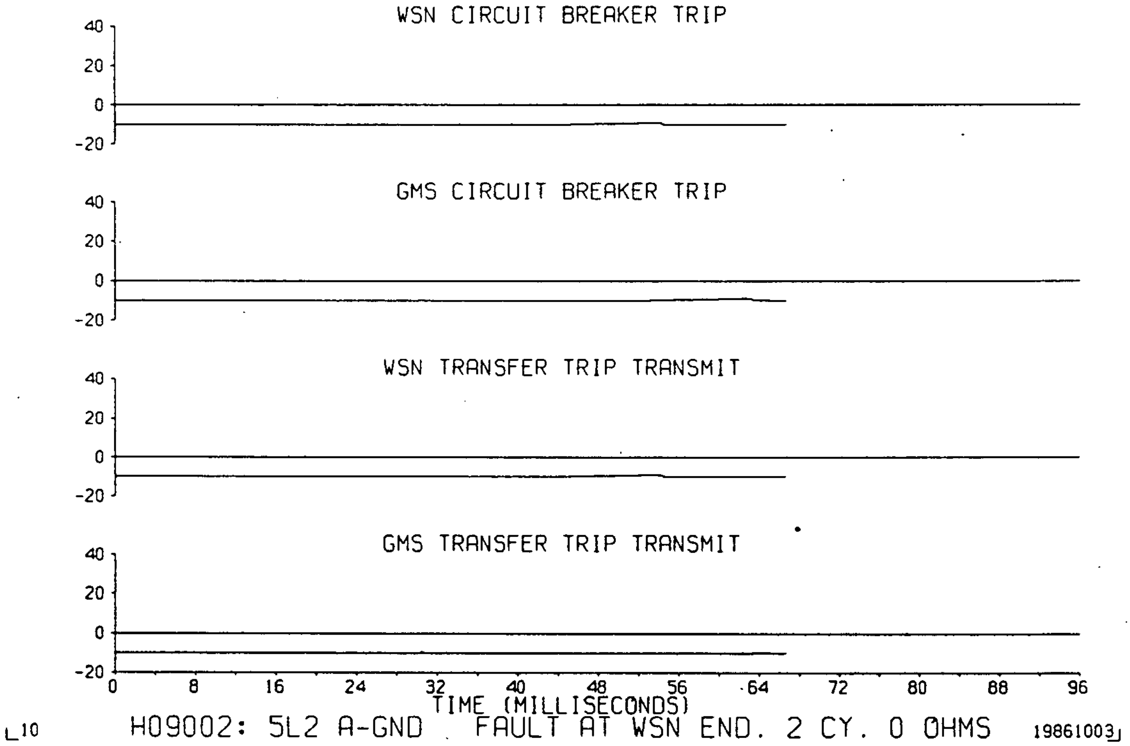

Fig. 18(j). Transfer trip and Williston circuit breaker trip waveforms

reversal in fault direction, thereby inhibiting a **local forward permissive** condition at Williston. This demonstrates the importance of the memory blocking feature of the Peace River protection.

Referring to fig. 18(e), the G.M. Shrum 21LX fault-detecting relay can be seen to operate 3 ms after the fault. The 21L2 overreaching distance relay can be seen to have some tendency to overreach prior to the insertion of a pickup delay under the control of the 21LX **insert delay** control output.

The G.M. Shrum ground-fault protection waveforms are shown in fig. 18(f). Forward directional element 32F is initially high due to load current, and remains high until the reversal in apparent fault direction after clearing at the Williston end of 5L2. Both low-set ground-fault relay 50LN/IOL and ground-permissive relay 50LN/IOH pick up on fault current.

The combination of 50LN/IOH and 32F establishes a **ground-fault permissive** signal prior to clearing at Williston, when the combination of 50LN/IOL and 32R establishes a **ground-reverse blocking** signal. These can be seen on fig. 18(g).

Figure 18(h) shows the **combined permissive** signal (resulting from the **ground-fault permissive** signal) which, as a consequence of the **no reverse blocking** signal, establishes a **local forward permissive** condition at G.M. Shrum. (It is this situation which the Williston blocking memory is needed to protect against.) The **local forward permissive** condition is suspended by the reversal of apparent fault direction due to the Williston-end clearing.

Figure 18(i) shows the G.M. Shrum **permissive trip transmit** signal which results from the **local forward permissive** condition. No corresponding condition exists at Williston (due to the reverse blocking memory) so that no trip condition results, as can be seen in fig. 18(j).

e. Case H09011

Case H09011 is for an internal 5L1 AC phase-to-phase fault at the Williston line end. The full power-system model was used. The fault was applied at 7.04 ms, corresponding to a point-on-wave angle of 143° between the faulted-phase voltages. Fault resistance is ignored.

Only one set of waveforms is given for this simulation, fig. 19, which shows the characteristic timing behaviour of the phase-fault protection for a close-up fault.

Note that 21L2 is the first of the SD-2H units to pick up at 13 ms after the fault, since it has the largest reach. Next to pick up is 21L1, at 16 ms after the fault. Of greatest interest here is 21L3, which picks up at 21 ms after the fault due to the offset static characteristic caused by the load angle compensator on this unit. The operation of 21L3 has been delayed by the shifted transient characteristic for reverse faults, which prevents the relay from seeing reverse faults until after decay of the memory polarizing voltage.

This is exactly analogous to the expanded transient characteristic described in the closure to Hayden et al. (1971), which gives memory polarized relays extended reach for a short interval after a fault, allowing their use on series compensated lines.

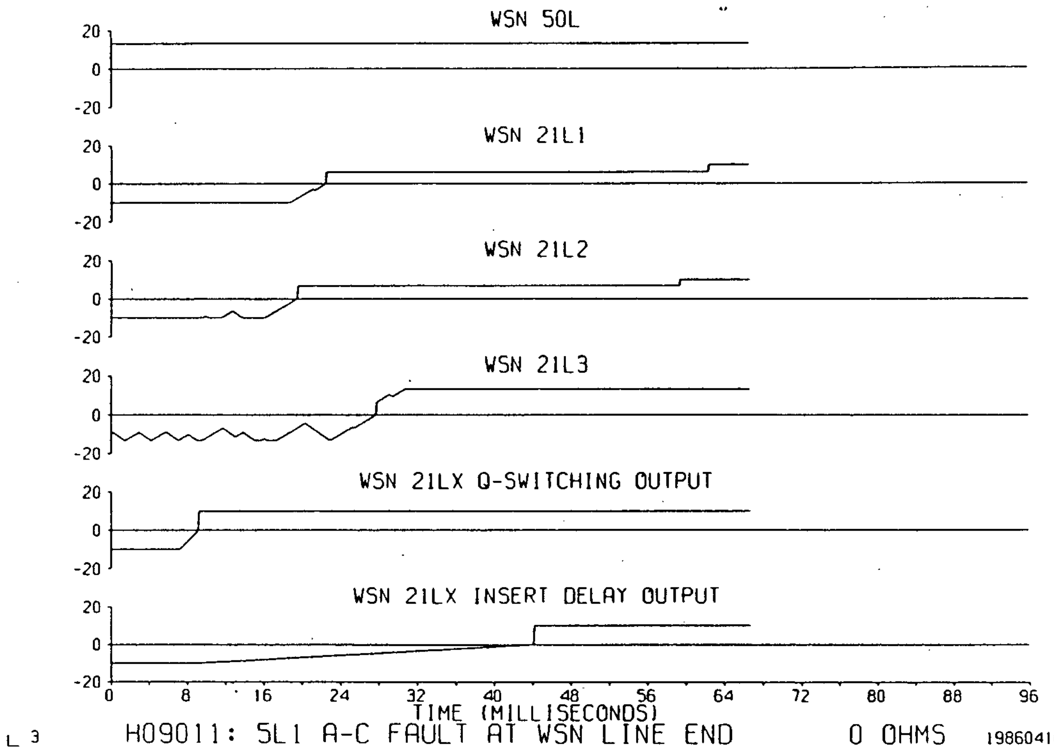

Fig. 19. Williston phase-fault protection waveforms for case H09011

2. Effect of System Truncation on Protection Response

a. Case H11002

Case H11002 is a repeat of case H09012 except that the reduced power system model is used. The 5L1 voltage and current waveforms for this case, along with the corresponding waveforms for case H09012 for comparison, are shown in fig. 20(a-d).

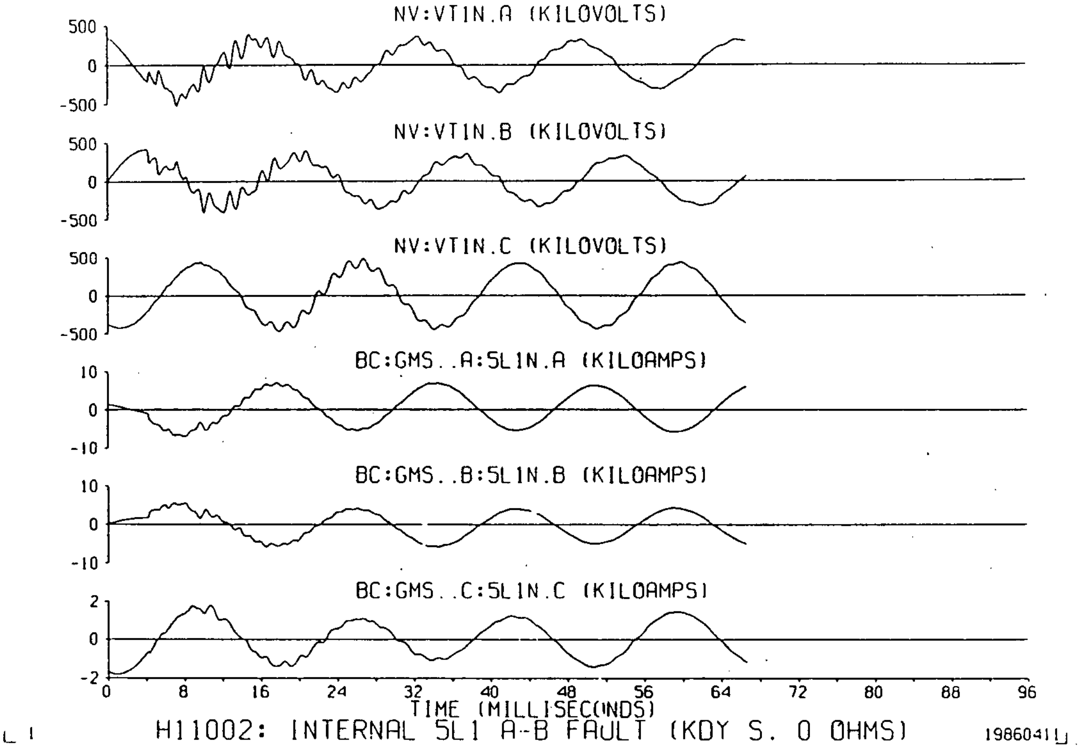

Fig. 20(a). G.M. Shrum-end waveforms for H11002

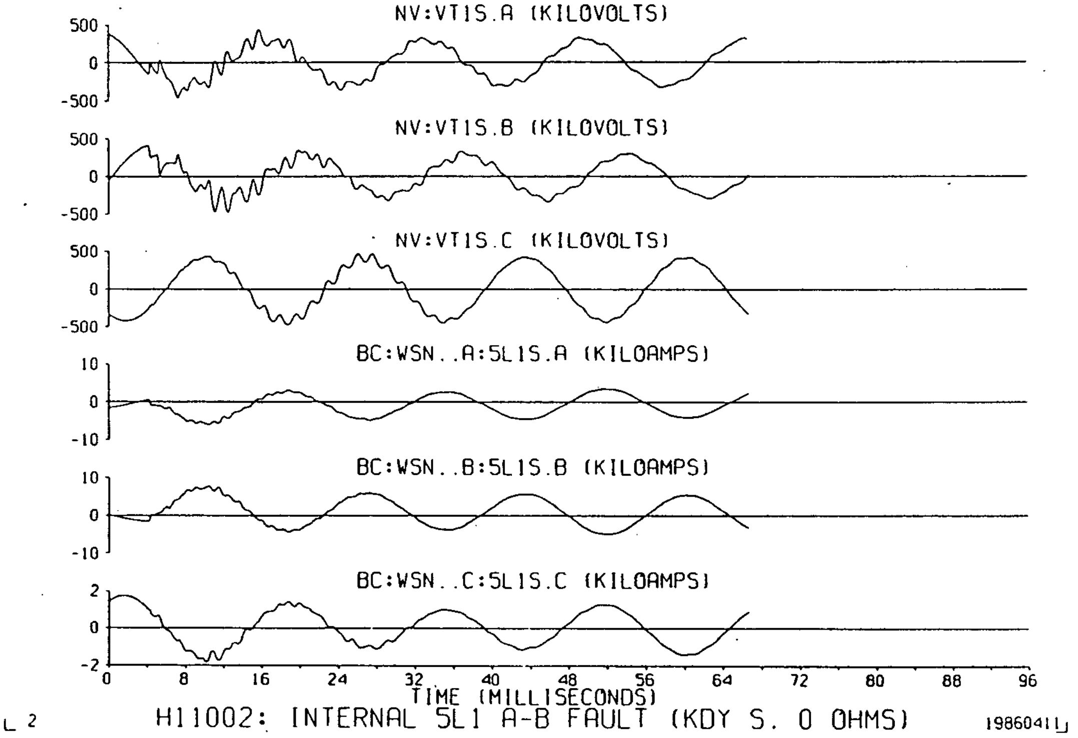

Fig. 20(b). Williston-end waveforms for H11002

Fig. 20. 5L1 waveforms for cases H11002 and H09012

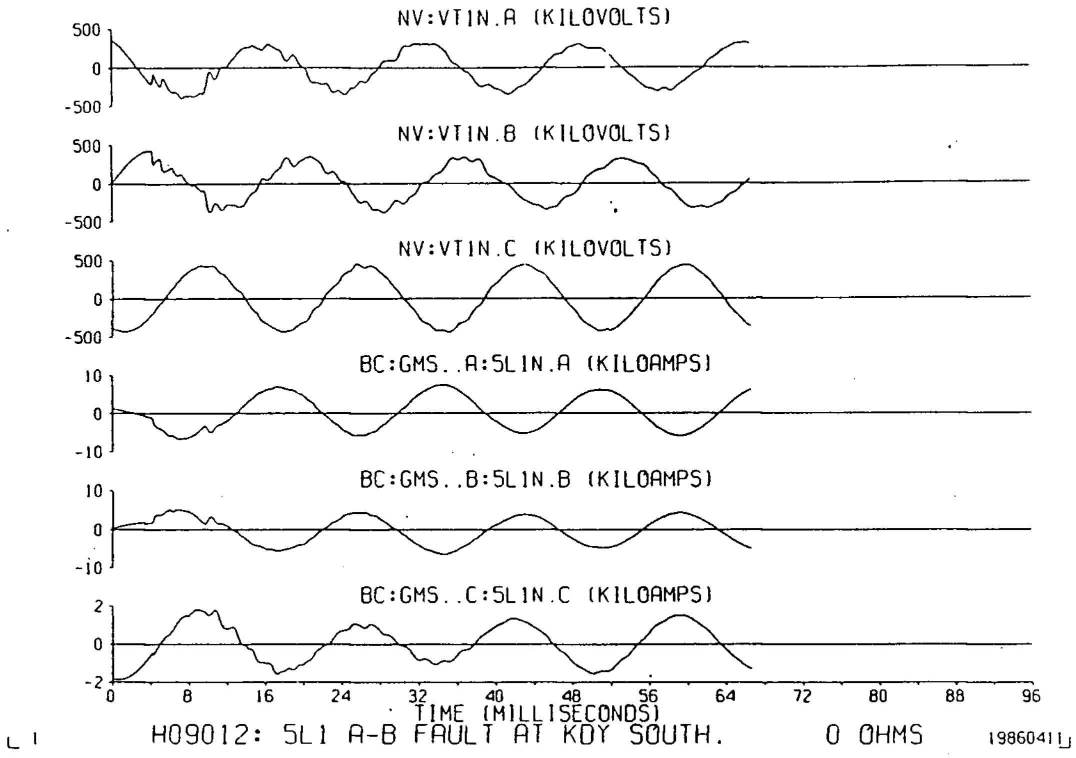

Fig. 20(c). G.M. Shrum-end waveforms for H09012

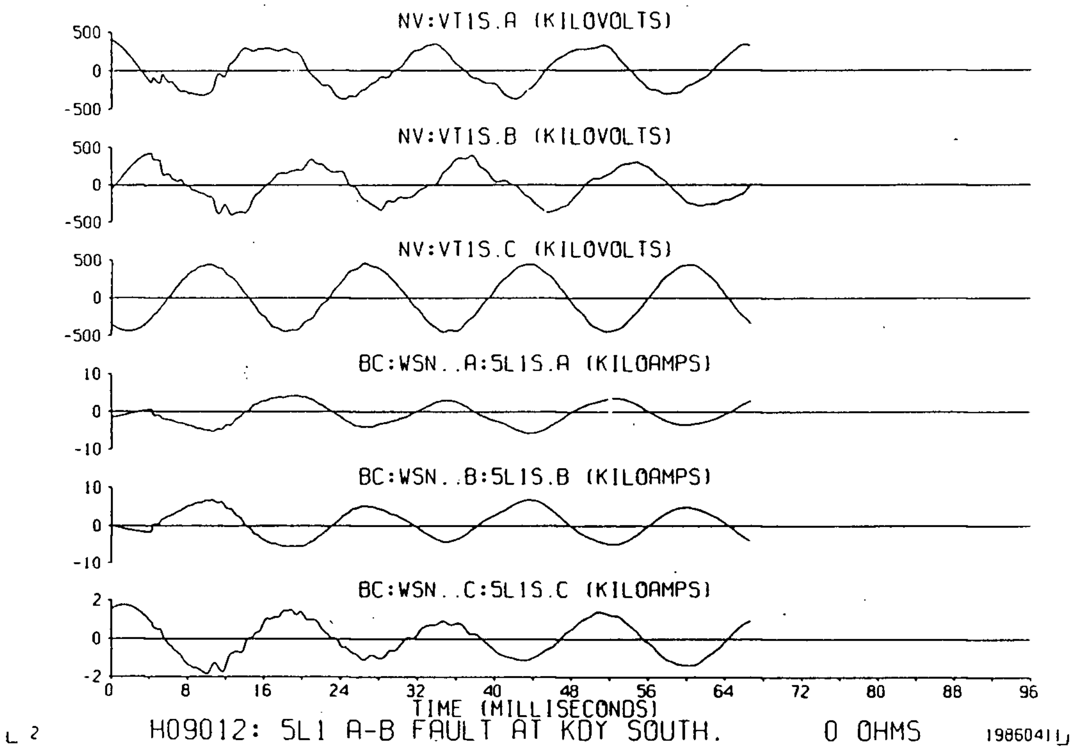

Fig. 20(d). Williston-end waveforms for H09012

The upper three traces in each of these figures are the phase A, B, and C voltages (top to bottom), while the lower three traces are the phase currents (in the same order). Figs. 20(a) and (c) show the G.M. Shrum waveforms, while figs. 20(b) and (d) show the Williston waveforms.

Comparison of the G.M. Shrum waveforms for H11002 in fig. 20(a) with the corresponding waveforms for H09012 in fig. 20(c) shows a distinct oscillation in the H11002 waveforms (at a frequency of approximately 600 Hz) which is absent in the H09012 waveforms. The amplitude of this oscillation is particularly severe in the voltage waveforms. Comparison of the Williston waveforms of figs. 20(b) and (d) clearly shows this same difference.

The distinctive oscillation is caused by reflection of fault-induced travelling waves from the power-frequency equivalent source at Williston. These reflections are incorrectly severe since the transmission lines of the actual system have been replaced by a series RL branch, which provides an impedance discontinuity which increases with frequency, behaving like a "brick wall" for high frequencies.

Ordinarily, high frequency oscillations such as occur in the waveforms for case H11002 would be expected to cause delays in relay operation (Johns and Aggarwal, 1977). The delays would in this case be unrealistic (since the high frequency oscillation itself is unrealistic).

The filters used in the 5L1 protection simulated here prevent the delays from occurring however. The values of Q for these filters were selected to ensure that the relays would operate correctly for the reduced-system model, in spite of the extreme high-frequency transient component. As a consequence, little difference was found in the operation of the protection for case H11002 as compared with case H09012.

This would not necessarily be the case with other power systems and protection however; the filtering for the SD-2H phase-fault relays is particularly heavy due to the problem with low-frequency series capacitor transients. Where only low-pass filters are used (rather than the bandpass filters used in the SD-2H), problems may be encountered with the low-frequency reflection transients characteristic of the actual system (as is the problem with the TEPCO system: Okamura et al., 1980; Kudo et al., 1985). Low-pass filtering which is effective for the artificially-high-frequency reflection transients of a truncated power system model may be inadequate for the lower-frequency transients characteristic of the actual system. Since the frequency and amplitude of reflection transients depend upon the termination details of the faulted line, the only general statement which can be made is that caution is required in modelling: it is safer to represent too much of the system than too little.

Comparisons between the protection behaviour with the full and truncated power system models were also made for a 5L1 phase-to-phase fault at Williston line-end and a 5L1 SLG fault on the north side of Kennedy series capacitor station. No significant differences were noted in these cases either in the protection responses or in the 5L1 waveforms. The reason for the 5L1 waveform similarity in the case of the Williston line-end phase-to-phase fault is probably due to the effective severing of the faulted phases of 5L1 from the system behind Williston (by the fault), so that the extent of that modelling is irrelevant. For the SLG fault at Kennedy, the reason for the similarity was probably the high ground-fault resistance, which reduced the magnitude of fault-induced transients as compared with the power-frequency voltages and currents. This was not pursued further since the lack of frequency dependence for ground mode propagation would result in incorrectly-low damping of the high frequencies, so that the apparent differences between the 5L1 waveforms for the full and truncated models would be greater than is actually the case. The lack of frequency-dependent modelling is not a significant concern for phase faults.

CHAPTER VII. CONCLUSION

A. DIFFICULTY OF CREATING POWER SYSTEM AND RELAY MODELS

Power system models for simulation of transient conditions can be time-consuming to prepare, due particularly to the difficulty of assembling the necessary data. This data is much more extensive than that required for the more-conventional fault, power-flow, and stability simulations.

Fortunately it is becoming relatively common to do lightning and switching-surge studies using digital simulation, so that some system models may already be available. Where this is the case, a great deal of effort can be saved in setting up the transmission system, although some modelling improvement may be required in the immediate study area. The operating conditions will likely have to be adjusted in any case, so that considerable effort can still be required.

Altering system operating conditions can be tedious, since many (if not all) Thevenin equivalents will require some adjustment, at least of the voltage. The fault levels must then be matched to conventional fault study results, and the pre-fault power flows must be matched to power-flow program results, so that several man-days can easily be required.

The major problem generally lies with the preparation and testing of any required multi-bus Thevenin equivalents. This can take as much as one or two man-days even for a two-bus equivalent. The need for multi-bus equivalents decreases where the system is largely radial—the usual situation for major new generation, where extensive studies are most likely to be required.

Since new transmission line models are always prepared from raw data, it is reasonable to allow at least half a man-day for each set of coupled lines required.

Where transient-event simulations are being conducted for the first time, the task of compiling the necessary data can be enormous. Once this has been done, however, the resulting system model can be updated from year to year along with the usual fault-study, power-flow, and stability models. The advantages of "base case" data files are as great here as for the more-conventional simulations.

The author prepared the full-system B.C. Hydro model used for the simulations of chapter VI by piecing together transmission from separate switching-study data cases, adding or deleting transmission lines as required to obtain the system representation for the desired study year, and then preparing the necessary Thevenin equivalents. (Detailed comments appear in the data listings in appendix A.)

Relay models can also be time-consuming to prepare. Fortunately, however, relays tend to be of standard types, and are more "shareable" between utilities than power system models.

Ideally, manufacturers would provide suitable FORTRAN-callable models for their relays, at least for the newer designs. It is more likely, however, that the necessary models will have to come from utilities and universities.

The advantages of developing models of specific relays using a good relay test facility (capable of determining relay response to transient events) cannot be over-estimated. The best modelling always results from "closing the loop", where the performance of the model is compared with that of a representative relay under identical conditions. In most cases, however, models will have to be developed with no possibility of exact comparison with a representative relay. (This was the case for the models used for the simulations of chapter VI.)

Models developed without test facilities can still provide a reliable indication of the performance of the protection as a whole. A robust protection scheme cannot be sensitive to the behavioural subtleties of the relays used. Protection schemes are generally designed in terms of functional requirements for the relays. Such requirements as operating principle, setting range, speed, and, in a general way, relative insensitivity to expected transients, can be specified without going into the details of relay design. If the model relay meets the necessary functional requirements, the overall protection performance should be substantially the same as with the actual relay.

In the initial stages of protection planning the functional requirements of the relays will not, in any case, be completely known (it being the point of the simulations to determine what they must be). In this case, functional modelling is entirely appropriate.

Models for generic relay types (such as the overcurrent and directional element models used in this project) are relatively fast to develop, taking of the order of one or two man-weeks, or even less if they are built up of subroutines already developed for other models. Models for specific relays (such as the SD-2H model used in this project) generally take much longer, one or two man-months being a reasonable estimate even with extensive use of subroutines developed for other models. Naturally, the more comprehensive the model library becomes, the faster new models can be developed.

B. COST OF POWER SYSTEM AND PROTECTION SIMULATION

One of the advantages of NLR techniques is that the total number of simulations required is kept to a minimum. This is an important advantage, since the digital simulation of large systems is relatively expensive.

Power system simulations using the University of British Columbia version of the EMTP (with dimensions increased from the general-use version) and the large power-system model took about 37 s of CPU time on the UBC Amdahl 5860 (with FPU) running MTS. Similar simulations using the smaller power-system model took about 12 s of CPU time, or 33% of the large system time. The TRP simulation of the protection system took about 30 s of CPU time, or 80% of the large system simulation time. Comparable runs on a VAX 780 running VMS showed times about 20 times greater.†

As dimensioned for the simulations of chapter VI, the TRP takes approximately 0.6 MByte of virtual memory. This is when compiled using the IBM compiler, which assigns all variables as static in storage. Compilers which assign subroutine local variables as dynamic will use less memory.

Certain aspects of the TRP are now known to be less efficient than they could be, so that the CPU times for TRP execution can be considered conservative. Nevertheless, as a general guideline, the cost of a protection simulation can be considered to be approximately the same as the cost of a (well-modelled) power-system simulation.

†Subsequent testing at B.C. Hydro showed that the CPU requirements for simulations of the full power system model and the 5L1 protection were comparable with requirements for typical transient stability simulations.

C. SUMMARY OF FINDINGS

The findings of this research, and the conclusions which may be drawn from them, are as follow:

1. Numerical logic replacement (NLR) is a practical method of determining the tendency of a complex protection system to misoperate for simulated faults. The operating tendencies of individual relays (as reflected in their pseudo-outputs) are propagated through the protection scheme logic to the circuit-breaker trip signal. Misoperating tendency is thus visible from a single waveform. The information which can be extracted from a single simulation is greatly increased.

2. The simulation of complex, multi-relay protection schemes on digital computers is both feasible and (for a moderate number of individual simulations) practical. The practicality is significantly improved by using NLR, since impending protection insecurity can be seen directly from the circuit-breaker trip waveforms (see discussion of case H10006 in chapter VI). The number of simulations needed to ensure protection security and dependability is thus significantly smaller than when the scheme logic is represented directly using Boolean logic. For the same reason, significantly greater confidence can be placed in the conclusions drawn from a series of simulations.

3. Protection simulation is essential to ensuring protection security. It is essential to ensuring dependability with heavily-filtered memory-polarized mho relays when the expanded reach of the transient mho circle is to be relied upon.

4. Simulation cost and memory requirements are moderate. Combined simulations of the power system and the protection for one transmission line require comparable CPU time to a transient stability simulation. As dimensioned for the simulations described in chapter VI, the protection simulator (TRP) requires less than one megabyte of virtual memory.

5. Simulated protection behaviour was found to agree generally with the known behaviour of the actual scheme, indicating that "semi-specific" modelling† for the principal fault-detecting relays and generic modelling for the remaining relays can produce satisfactory results for protection application studies. This was found to be true in spite of certain known differences between the models and the actual relay hardware, suggesting that practical protection schemes are not strongly sensitive to the subtleties of individual relay behaviour. (This does not imply, however, that relays for industrial simulations need not be modelled as carefully as is practical.)

   Where it is possible to compare the performance of the actual relays (using a relay test facility, for example) with the performance of the models under identical conditions, this should be done. This comparison would have been especially valuable for determining the memory and IZ-V input filter Q values for the SD-2H relays simulated for this research. These values could not be adequately

†As was used for the SD-2H, for example, where only certain portions of the relay (input filters, special output logic, etc.) were modelled directly from the actual hardware. The remaining portions of the relay (e.g. the comparator) made use of generic models.

determined by test simulations using the model alone.

6. Careless truncation of the power system during modelling can result in gross errors in the transient components of the simulated voltages and currents applied to the protection. The extent to which this will produce errors in the protection simulations depends on factors such as fault location, relay location, and the sharpness of relay input filters.

7. "Sequential" simulation may be successfully employed for fault application studies. (The "simultaneous" technique must be used to model feedback loops within the sequential simulation.) "Sequential" simulation may be used for studies of external fault application and clearing, provided that realistic clearing times have been pre-determined and included in the power system simulations (i.e. the simulations are performed in two steps).

8. Generic models of uncomplicated relays can often be developed in one or two man-weeks. This time can be reduced by making use of a library of basic relay functions (single-input amplitude comparator, memory/filter circuit, etc.). One or two man-months can be required to develop models for the specialized portions of more sophisticated, specific relays (e.g. the SD-2H), even when a library of basic relay functions is available.

9. Finite sensitivity for current inputs can be modelled by using overcurrent relays operating "gate" elements in the current input circuit. For models of specific relays, the sensitivity could be more-efficiently

included directly in the model, preferably as an adjustable parameter.

D. DIRECTIONS FOR FUTURE WORK

a. Numerical Logic Replacement

Further work is needed to determine the best NLR implementation of devices, such as timers, which use the output of other relays as input. There is a danger in this situation that a near start-up of the controlled-device (e.g. the timer) will not be indicated in the device output. For example, if a delayed-pickup timer were specified with a pickup delay of zero, it would be completely transparent in the logic flow. If the output did not reflect the level of the NLR input, a near operation (which could be significant to decision reliability) might not be visible in the output.

While this specific case of a timer with zero delays is improbable, substantially-similar situations may occur in practice. These situations must be identified and resolved by developing appropriate NLR implementations for controlled devices. (Although the timer implementation used herein is believed to be satisfactory, there is not yet sufficient experience with it to be completely confident.)

A second area of concern is hysteresis, which tends to obscure the amount by which a relay has operated (crossed its decision threshold). This may not be a serious practical problem; it may, however, be a chronic limitation of NLR, as remains to be established.

b. Better Data for Use in Simulations

Standard methods are needed for describing the transient behaviour of instrument transformers completely enough to allow suitable modelling. The adoption of standard models may be required. The model parameters could then become standard device specifications.

Related to the need for better instrument transformer data is the need for better burden data. This is a more difficult task, since real burdens are completely installation-dependent. Field measurements, and sensitivity studies with various degrees of modelling detail, are required in this area.

c. Proven Relay Models

With the superb facilities which now exist for relay testing, it is possible to develop proven, FORTRAN-callable models for popular relays. The development of such models would be of tremendous service to the industry. With wide distribution the development cost could be spread over many users.

Ideally, digital models of new relays would be provided by the manufacturers, a task simplified by the fact that almost inevitably some digital modelling will be carried out prior to the construction of a hardware prototype anyway (Muller, 1980; Chamia and Hillström, 1983; Engler et al., 1985). As more commercial digital relays appear on the scene, the provision of digital "models" will become simpler, and, one hopes, standard practice.

Meanwhile, however, many older relay designs are in use for which models will be required.

d. Sensitivity Analysis for Modelling Detail

Careful analysis is required of the effects of various degrees of modelling detail on relay input waveforms, and on the response of standard relay designs. Although some analysis has been already done by various researchers, there remains a need for the coordination of further research and a summary of the results.

E. CONTRIBUTIONS OF THIS RESEARCH

There are three principal contributions of this research:

1. Numerical logic replacement (NLR) has been shown to be a practical method for significantly increasing the information available from individual protection simulations, thus permitting a reduction in the total number of simulations required to establish protection security and dependability.

2. The simulation of comprehensive protection schemes on a digital computer has been shown to be feasible, and computation requirements for individual simulations have been shown to be moderate.

3. A digital protection simulator has been developed which is suitable for use in industrial protection simulations.

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APPENDIX A

POWER SYSTEM MODEL

A. *B.C. HYDRO 500 KV SYSTEM*

Two power system models were used for the simulations. The "full system" model includes the bulk of the 500 kV transmission; one-line diagrams can be found in figs. 4 and 21(a-c). (A list of the station abbreviations is given in table 3.)

The second, "reduced system" model consists only of the G.M. Shrum to Williston transmission (fig. 4), and uses a Thevenin equivalent for the system south of Williston. The reduced system model was used to investigate the effects of system truncation on simulation results.

Transmission line models for the Peace transmission are distributed-parameter models with discrete transposition, and full mutual coupling between phases and parallel lines. Line constants are treated as constant with respect to frequency, and have been computed at 60 Hz (for proper steady-state results). The constant parameter assumption can be expected to result in damping below actual levels for ground-mode propagation. No significant errors are to be expected for aerial propagation modes.

Transmission lines away from the immediate study area are modelled either as continuously-transposed distributed-parameter lines, or using coupled pi-sections. Mutual coupling has been ignored between the parallel lines connecting the B.C. Hydro system at Ingledow substation and the "equivalent" representation for the Bonneville Power Administration system at Custer and Monroe.

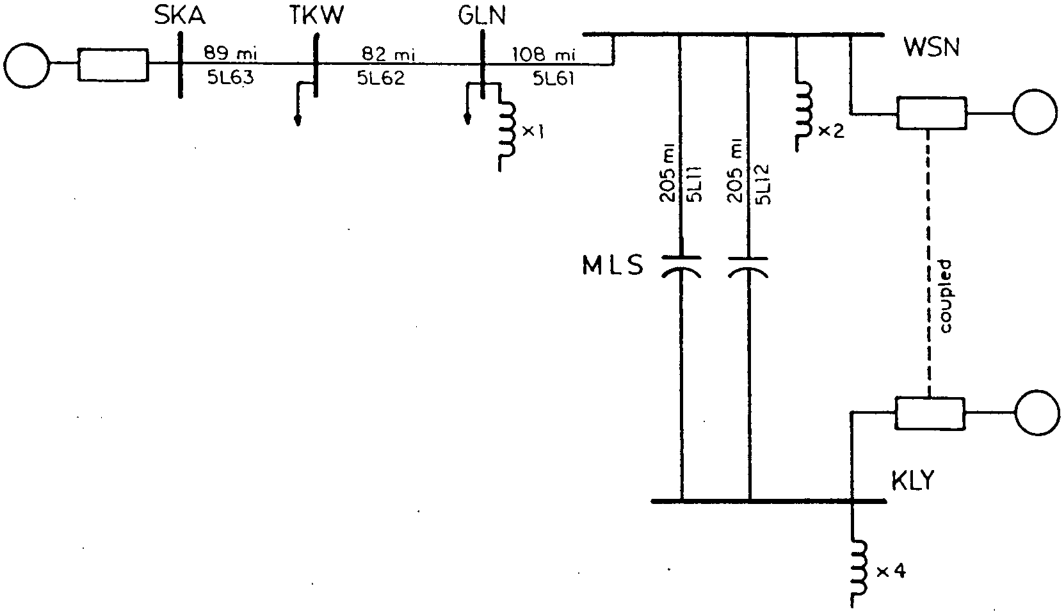

Fig. 21(a). Transmission system south of Williston to Kelly Lake and west to North Coast.

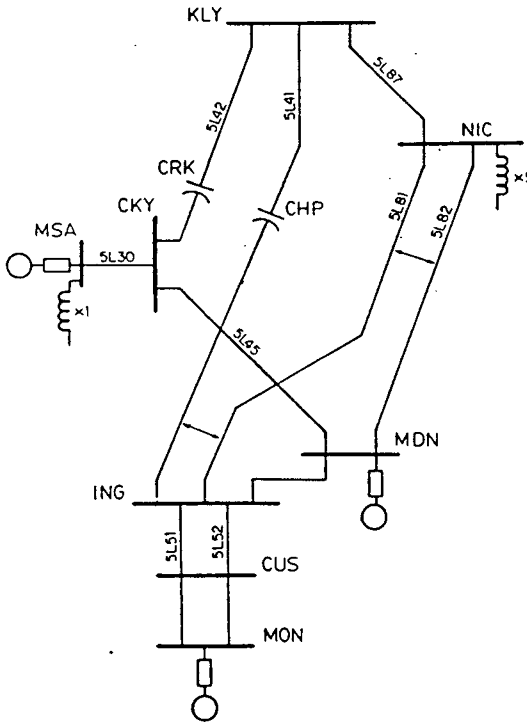

Fig. 21(b). Transmission system south from Kelly Lake and east to Nicola.

Fig. 21. One-line diagrams for B.C. Hydro power system, as modelled.

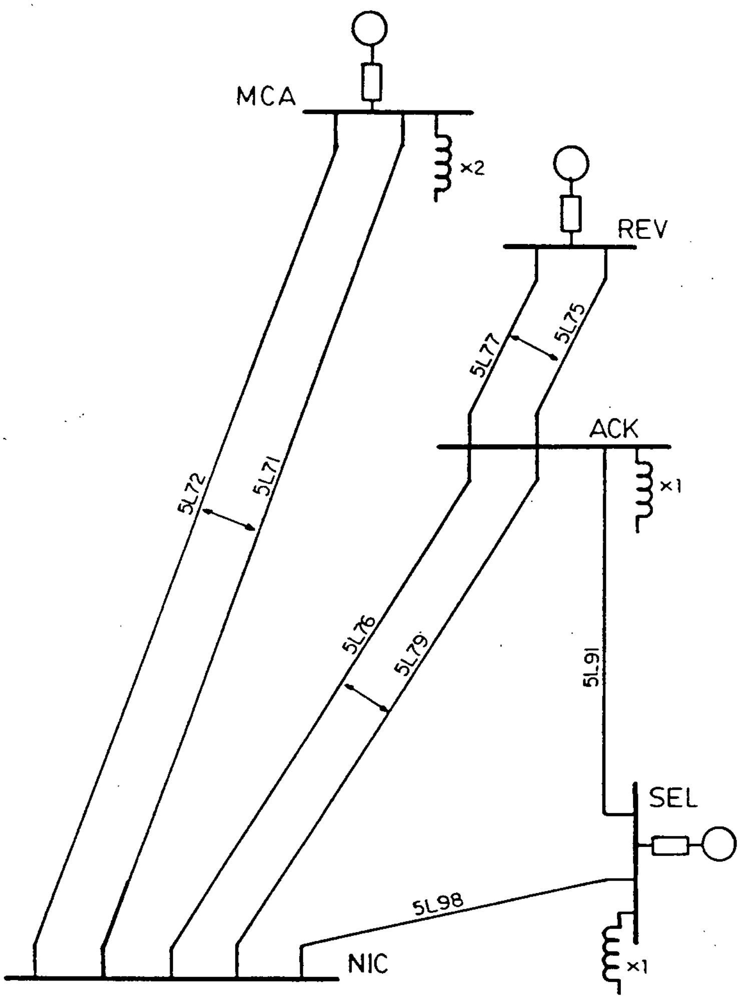

Fig. 21. (c) Transmission system from Mica and Revelstoke to Nicola.

The EMTP distributed-parameter line model uses linear interpolation between "past-history" values from the opposite end of the line as a part of the solution process. This causes some interpolation error. In setting up this simulation, the lengths of transmission lines in the immediate study area were adjusted slightly so that interpolation would be small, and approximately equal for both aerial and ground modes. This resulted in 5L1, 5L2, and 5L3 being

TABLE 3

List of Abbreviations for Station Names

Abbreviation	Station Name
ACK	Ashton Creek Substation
CHP	Chapmans Series Capacitor Station
CKY	Cheekye Substation
CRK	Creekside Series Capacitor Station
CUS	Custer station (Bonneville Power Administration)
GLN	Glenannan Substation
GMS	G.M. Shrum Generating Station
ING	Ingledow Substation
KDY	Kennedy Series Capacitor Station
KLY	Kelly Lake Substation
MCA	Mica Generating Station
MDN	Meridian Substation
MLS	McLeese Series Capacitor Station
MON	Monroe station (Bonneville Power Administration)
MSA	Malaspina Substation
NIC	Nicola Substation
PCN	Peace Canyon Generating Station
REV	Revelstoke Generating Station
SEL	Selkirk Substation
SKA	Skeena Substation
TKW	Telkwa Substation
WSN	Williston Substation

modelled as 170 miles in length (about 1% low).

The interpolation also limits the minimum length of distributed-parameter line representations; the transit time for the fastest mode must be at least as great as one time step for the study. Thus the length of 5L4 has been increased by about 5 km (40%), and the length of one section of 5L30 from Cheekye to Malaspina has been increased by about 0.3 km (3%).

Loads, subtransmission level portions of the system, and parts of the system remote from the immediate area of study (such as the Vancouver Island system, and the Bonneville Power Administration system in the United States of America) were replaced by three-phase Thevenin equivalents. These equivalents were computed at 60 Hz. In most cases, the equivalent was connected to only a single bus, so that buses were not coupled through the equivalents. This is common practice for industrial switching-surge simulations.

In the case of Kelly Lake and Williston, however, single-bus equivalents were inadequate, since there would be no allowance for 230 kV transmission (not represented in detail) between the two buses (see fig. 22). A two-bus (six phase) Thevenin equivalent was used in this case. The voltages at Williston and Kelly Lake thus reflected the contribution of flows on the 230 kV transmission to the fault current. (Mutual coupling between the 230 kV and 500 kV transmission systems was not accounted for in the equivalent.) The use of equivalents is discussed in chapter IV.

1. Series Capacitors

All series capacitor installations are for 50% compensation of the line in which they are installed, with the single exception of Creekside. Protective gaps are installed at all series capacitor installations to bypass currents of dangerously high magnitudes (Batho et al., 1977; Mansour et al., 1983). These gaps have been modelled only at Kennedy (for 5L1, 5L2, and 5L3), since for faults considered herein, gap flashing can occur only for these lines. For all other lines with series compensation, only the effective series capacitance is modelled (i.e. gap flashing is suppressed).

Figure 23 shows the detailed model for the series capacitor banks in 5L1,

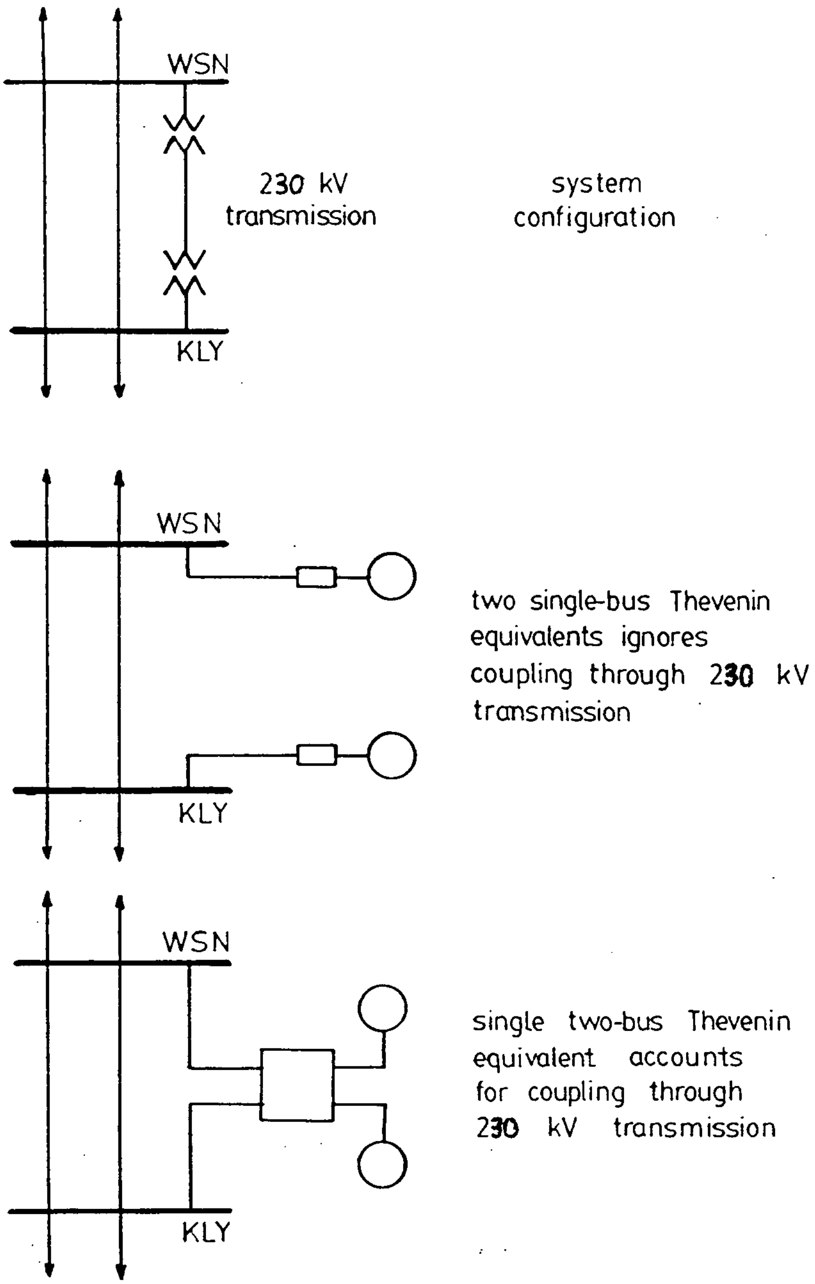

Fig. 22. Derivation of two-bus Thevenin equivalent for Williston and Kelly Lake

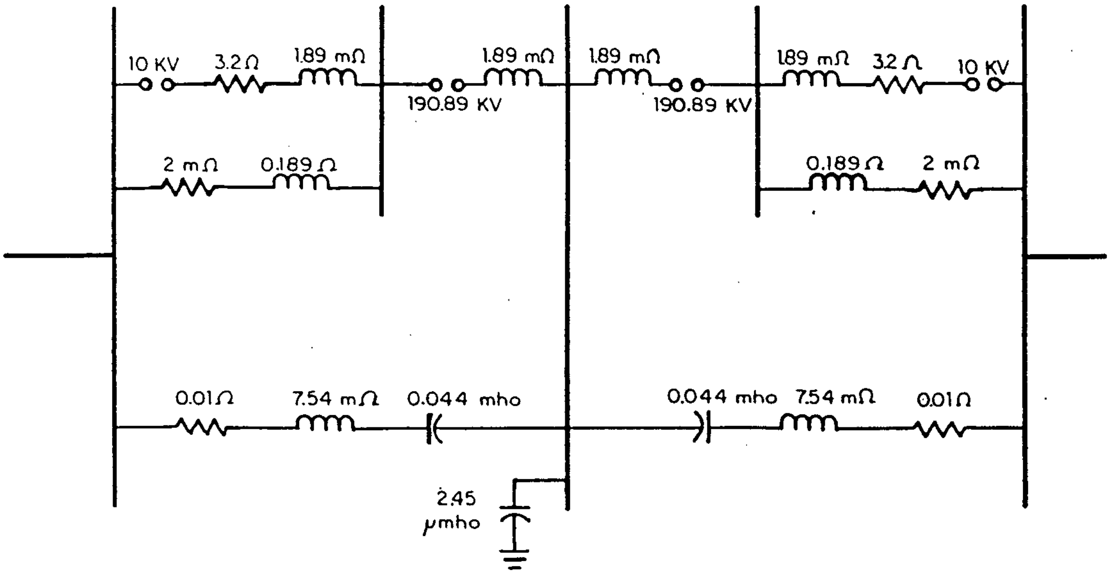

Fig. 23. Series capacitor detail for 5L1 and 5L2

5L2, and 5L3. The main protective gap setting of 190.89 kV shown is for 5L1 and 5L2; the correct setting for 5L3 is 192.42 kV.

2. Shunt Reactors

Shunt reactors are single-phase units connected in grounded-wye, except where single-pole reclosing is employed. The standard reactance value is 2040Ω per bank.

Shunt reactors are installed on the associated line, rather than the bus. This distinction was made in the power system model only for 5L1 and 5L2, since for 5L1 the line current must include reactor current, and for 5L2 the reactors must be cleared when the line is cleared. For all other lines, no distinction between bus and line end is required.

3. Generator Equivalents

Generators are modelled as E" behind X_d'', as for conventional (steady-state) fault studies. No attempt has been made to account for generation detail (governors, exciters, etc.). Time constants R / L_d'' associated with generation are not known, but a standard value used in B.C. Hydro specifications is 0.1 s. The resistive component of generator Thevenin equivalent impedances has thus been computed to obtain a 0.1 s time constant.

Braking resistance at G.M. Shrum has not been included in the power system model.

4. System Operating Conditions

Operating conditions for the study correspond to heavy load conditions for Peace River generation. The resultant loading on the line under study (5L1) is 1200 MVA at a power factor of 95% (as measured at the G.M. Shrum end).

The generator internal voltages E" were computed to produce power flows consistent with power flow program results for the operating condition selected.

5. Derivation of Two-bus Thevenin Equivalent at Williston and Kelly Lake

The desired Thevenin equivalent is six-phase, and is described by the matrix equation:

$$\bar{E} - \bar{V} = [Z]\ \bar{I}$$

where

$\bar{E}$ is the vector of Thevenin internal (open-circuit) phase voltages at Williston and Kelly Lake

$\bar{V}$ is the vector of phase voltages observed at the external buses at Williston and Kelly Lake

$[Z]$ is the Thevenin impedance matrix, and

$\bar{I}$ is the vector of phase currents flowing into the external buses from the equivalent.

Vectors $\bar{E}$, $\bar{V}$, and $\bar{I}$ are all six-element vectors, and matrix $[Z]$ is 6×6.

The six columns of $[Z]$ can be computed from the results of six SLG fault solutions (one for each of the three phases at each of the two buses, see fig. 22) from a conventional (steady-state) fault analysis program. A phase "j" SLG fault produces a fault current I_j and a corresponding voltage vector $\bar{V}_j$. The Thevenin internal voltage $\bar{E}$ is one per unit pure positive sequence at both buses for conventional fault analysis programs. The elements of $[Z]$ can then be computed from

$$Z_{ij} = (E_i - V_i) / I_j.$$

The Thevenin internal voltage $\bar{E}$ to be used for the equivalent is then computed from

$$\bar{E} = [Z]\,\bar{I} + \bar{V}$$

where

$\bar{I}$ is the vector of phase currents out of the equivalent under pre-fault conditions, and

$\bar{V}$ is the vector of pre-fault voltages at Williston and Kelly Lake buses.

6. Derivation of Equivalent South of Williston

The equivalent south of Williston is a simple three-phase single-bus Thevenin equivalent. The impedance matrix for this equivalent was obtained from fault study results for an SLG fault at Williston. The elements of the matrix were computed from the (power-frequency) positive- and zero-sequence impedances of the equivalenced network, as seen from Williston. The Thevenin internal voltage $\bar{E}$ was computed as for the Williston/Kelly Lake equivalent, from the steady-state voltage and current at Williston.

7. Simulation Step Size and Duration

The size of the time-step for the study was 65 μs. The maximum theoretical study bandwidth would thus be $\simeq$7.7 kHz (based on the Nyquist requirement of two samples per cycle of the highest frequency). The modelling used (e.g. assumption of frequency-independent line parameters, lack of special transformer models) does not produce accurate results over this range, however. Lack of frequency-dependent line models is the most serious cause of inaccuracies. For single line to ground faults, in particular, damping at frequencies above 60 Hz is unrealistically low, so that high-frequency effects decay much more slowly than would actually be the case. Similarly, damping at frequencies below 60 Hz is unrealistically high, so that low-frequency effects decay more rapidly than would actually be the case. Since the relay filtering greatly reduces the impact of the high and low frequencies on relay operation, however, protection performance should not be seriously affected by the use of constant-parameter modelling.

Total duration of the simulation was 4.0 cycles, which was sufficient to allow the protection to operate in all but one case (for which the simulation time was extended to 6.3 cycles).

8. Listings of Full- and Equivalent-case Data for EMTP

Listings of the EMTP data for the full and reduced (equivalent south of Williston) power system models are provided in figs. 24 and 25, respectively.

```
Listing of SH09012 at 10:46:00 on APR 12, 1986 for CCid=BRWG                                                    Page   1

HO9012: 5L1 A-B FAULT AT KDY SOUTH,       0 OHMS     :                  2  60.   60.
65.10417-666.66667-3 -1  0  1         00
C65.10417-666.66667-3 -1  0  1         00
C                                                    :
C------------------------------------------------------
C Compiled: 19860410                     Source: H09003 -
C                          INTERNAL-FAULT              -
C                                                       -
C     DL  fault on KDY1SA--KDY1SB                        -
C         Fault resistance:   0   Ohms                   -
C         Point-on-wave:     143.13 degrees of KDY1S Vab -
C         Fault instant:     3.7805 msec                 -
C                                                       -
  KDY1SAFAULT1                 0.001                                       1
  KDY1SBFAULT2                 0.001
C------------------------------------------------------
C
C   19860307: GMS reactors moved from bus to 5L1 and 5L2
C
C     Peace River simulation. Full 1984 500KV B.C. Hydro network from
C Jack Sawada of B.C. Hydro, supplemented by Peace transmission
C lines extracted from a case from Brent Hughes of B.C. Hydro.
C (All data applies to 1984 system, and was obtained 13 Sept. 1985.)
C North Coast transmission is original data.
C Thevenin equivalent sources for GMS, PCN, WSN, REV, ACK, NIC, MCA,
C MSA, GLN, TKW, SKA, MDN, ING, SEL, CKY, and KLY were
C obtained from SLG fault study results from B.C. Hydro.
C
C     Study step size is 65 microseconds, giving a study bandwidth
C of about 5 KHz. Study simulation time is 67 milliseconds,
C corresponding to four power-frequency cycles. There are 256
C time points/cycle.
C
C     Transmission-line lengths for Peace River transmission have
C been adjusted to produce equal past-history interpolation
C requirements for both positive and zero sequence, so as to
C minimize errors caused by linear interpolation within program.
C
C     Peace River electrical network follows:
C
C     GMS Thevenin source:
C        (GMS-E is GMS internal voltage node)
C     GMS X/R ratio is based on B.C. Hydro standard CT specification
C        allowing for 0.1 second time constant (-> X/R=37.6999)
C   .    Thus ZS has 2.65% R added.
 1GMS-EAGMS..A             .5756 21.700
 2GMS-EBGMS..B                   -5.227       .5756 21.700
 3GMS-ECGMS..C                   -5.227             -5.227       .5756 21.700
C
C     GMS shunt reactors (2 units--one each 5L1 and 5L2)
  VT1N.A                  5.0   2040.
  VT1N.B      VT1N.A
  VT1N.C      VT1N.A
  VT2N.A      VT1N.A
  VT2N.B      VT1N.A
  VT2N.C      VT1N.A

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 24. Listing of EMTP data for full power system model

```
C
C     5L1 CT is from GMS to 5L1N
C     5L1 CVT is at VT1N
C
C     North end 5L1 closing resistors and switch-isolating impedances
C       Also used for current measurement
  GMS..A5L1N.A                  0.01                                           1
  GMS..B5L1N.BGMS..A5L1N.A                                                     1
  GMS..C5L1N.CGMS..A5L1N.A                                                     1
  CB1N1ACB1N2AGMS..A5L1N.A
  CB1N1BCB1N2BGMS..A5L1N.A
  CB1N1CCB1N2CGMS..A5L1N.A
  CB1N1AVT1N.A            400.
  CB1N1BVT1N.BCB1N1AVT1N.A
  CB1N1CVT1N.CCB1N1AVT1N.A
  GMS..A5L2N.AGMS..A5L1N.A
  GMS..B5L2N.BGMS..A5L1N.A
  GMS..C5L2N.CGMS..A5L1N.A
  CB2N1ACB2N2AGMS..A5L1N.A
  CB2N1BCB2N2BGMS..A5L1N.A
  CB2N1CCB2N2CGMS..A5L1N.A
  CB2N1AVT2N.ACB1N1AVT1N.A
  CB2N1BVT2N.BCB1N1AVT1N.A
  CB2N1CVT2N.CCB1N1AVT1N.A
C
C     5L1 AND 5L2 from GMS to junction with 5L3 from PCN
C        Data length-adjusted from Brent Hughes case, lengths
C         in miles. Untransposed line model.
-1VT1N.CL1-1.C            0.5877780.310988E4 26.00 1   6
-2VT1N.BL1-1.B            0.0421433.681589E4 26.00 1   6
-3VT1N.AL1-1.A            0.0403283.781798E4 26.00 1   6
-4VT2N.CL2-1.C            0.0399274.951823E4 26.00 1   6
-5VT2N.BL2-1.B            0.0399230.431846E4 26.00 1   6
-6VT2N.AL2-1.A            0.0400232.311847E4 26.00 1   6
 0.41879E 00-0.51633E 00-0.50625E 00 0.45368E 00-0.24886E 00-0.29476E 00
 0.37742E 00-0.39719E 00-0.12909E-01-0.16135E 00 0.54392E 00 0.57587E 00
 0.42676E 00-0.27482E 00 0.49348E 00-0.51708E 00-0.37640E 00-0.28544E 00
 0.42676E 00 0.27482E 00 0.49348E 00 0.51708E 00 0.37640E 00-0.28544E 00
 0.37742E 00 0.39719E 00-0.12909E-01 0.16135E 00-0.54392E 00 0.57587E 00
 0.41879E 00 0.51633E 00-0.50625E 00-0.45368E 00 0.24886E 00-0.29476E 00
C
C     PCN Thevenin source:
C        (PCN-E is PCN internal voltage node)
C     PCN X/R ratio is based on B.C. Hydro standard CT specification
C        allowing for 0.1 second time constant (-> X/R=37.6999)
C        Thus ZS has 2.65% R added.
 1PCN-EAPCN..A            2.496994.130
 2PCN-EBPCN..B                  -24.92      2.496994.130
 3PCN-ECPCN..C                  -24.92            -24.92     2.496994.130
C
C     PCN shunt reactors (1 unit):
  PCN..A                  5.    2040.
  PCN..B                  5.    2040.
  PCN..C                  5.    2040.
C
C     5L4 from PCN to GMS

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 24 (cont'd)

```
C         Data length-adjusted from solitary 5L3 data from Brent
C         Hughes case, lengths in miles. Untransposed line model.
C         Line length increase by 40% so travel time exceeds step
C         size.
C
-1PCN..CGMS..C              0.3229627.531188E4 12.03 1   3
-2PCN..BGMS..B              0.0489283.271806E4 12.03 1   3
-3PCN..AGMS..A              0.0488234.601847E4 12.03 1   3
 0.59747E 00-0.70711E 00-0.41230E 00
 0.53479E 00 0.20486E-12 0.81240E 00
 0.59747E 00 0.70711E 00-0.41230E 00
C
C      5L3 from PCN to junction with 5L1 and 5L2 from GMS
C         Data length-adjusted from Brent Hughes case,
C         lengths in miles. Untransposed line model.
-1PCN..CL3-1.C              0.3229627.531188E4 26.00 1   3
-2PCN..BL3-1.B              0.0489283.271806E4 26.00 1   3
-3PCN..AL3-1.A              0.0488234.601847E4 26.00 1   3
 0.59747E 00-0.70711E 00-0.41230E 00
 0.53479E 00 0.20486E-12 0.81240E 00
 0.59747E 00 0.70711E 00-0.41230E 00
C
C      5L1, 5L2, and 5L3 from junction to first transposition point:
C         Data length-adjusted from Brent Hughes case, lengths in
C         miles. Untransposed line model.
C      Transposition occurs at sending end of this line section
C         for 5L3
-1L3-1.AL3-2.A              0.8582895.000891E4 33.24 1   9
-2L3-1.CL3-2.C              0.0511497.861460E4 33.24 1   9
-3L3-1.BL3-2.B              0.0435409.941654E4 33.24 1   9
-4L1-1.CL1-2.C              0.0372253.001799E4 33.24 1   9
-5L1-1.BL1-2.B              0.0326205.261816E4 33.24 1   9
-6L1-1.AL1-2.A              0.0331215.861828E4 33.24 1   9
-7L2-1.CL2-2.C              0.0484232.461848E4 33.24 1   9
-8L2-1.BL2-2.B              0.0398229.131848E4 33.24 1   9
-9L2-1.AL2-2.A              0.0398231.091847E4 33.24 1   9
 0.32842E 00-0.44279E 00-0.38542E 00-0.31701E 00-0.48216E 00 0.23342E 00
-0.38674E 00-0.34537E-01-0.28830E-01
 0.29533E 00-0.37922E 00-0.25754E 00-0.41833E-01 0.70848E-01-0.11350E 00
 0.79290E 00 0.26841E-01 0.21073E-01
 0.33557E 00-0.36222E 00-0.10221E 00 0.27311E 00 0.54407E 00-0.29908E 00
-0.46379E 00 0.46756E-01 0.44760E-01
 0.35685E 00-0.13903E 00 0.42073E 00 0.44855E 00 0.47026E-02 0.53196E 00
 0.56800E-01-0.35236E 00-0.27719E 00
 0.32061E 00-0.15227E-01 0.45688E 00 0.29694E-01-0.19301E 00 0.13271E-01
 0.55685E-02 0.64282E 00 0.43423E 00
 0.35848E 00 0.10766E 00 0.43398E 00-0.41918E 00-0.10699E 00-0.53441E 00
-0.11166E-01-0.40051E 00-0.17183E 00
 0.34970E 00 0.37001E 00-0.82757E-01-0.43325E 00 0.39258E 00 0.29025E 00
-0.21875E-02 0.30158E 00-0.36355E 00
 0.30747E 00 0.39077E 00-0.24091E 00 0.13323E-01 0.84531E-01 0.13409E 00
 0.17366E-02-0.41258E 00 0.67345E 00
 0.34145E 00 0.45603E 00-0.36662E 00 0.44814E 00-0.34472E 00-0.26097E 00
 0.20493E-02 0.18335E 00-0.33728E 00
C
C      5L1 and 5L2 from first transposition point to KDY series

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 24 (cont'd)

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C          capacitor bank. Data length-adjusted from Brent Hughes
C          case, lengths in miles.
C      Transposition occurs at sending end for all three lines.
-1L1-2.BKDY1NB              0.5961780.300988E4 26.00 1   6
-2L1-2.AKDY1NA              0.0505433.631589E4 26.00 1   6
-3L1-2.CKDY1NC              0.0486283.781798E4 26.00 1   6
-4L2-2.BKDY2NB              0.0482274.771823E4 26.00 1   6
-5L2-2.AKDY2NA              0.0482230.261848E4 26.00 1   6
-6L2-2.CKDY2NC              0.0484232.311847E4 26.00 1   6
 0.41882E 00-0.51607E 00-0.50617E 00 0.45229E 00-0.25116E 00-0.29485E 00
 0.37737E 00-0.39742E 00-0.13064E-01-0.15798E 00 0.54457E 00 0.57589E 00
 0.42678E 00-0.27486E 00 0.49356E 00-0.51914E 00-0.37373E 00-0.28531E 00
 0.42678E 00 0.27486E 00 0.49356E 00 0.51914E 00 0.37373E 00-0.28531E 00
 0.37737E 00 0.39742E 00-0.13064E-01 0.15798E 00-0.54457E 00 0.57589E 00
 0.41882E 00 0.51607E 00-0.50617E 00-0.45229E 00 0.25116E 00-0.29485E 00
C
C      5L3 from first transposition point to KDY series
C          capacitor bank. Data length-adjusted from Brent Hughes
C          case, lengths in miles.
-1L3-2.BKDY3NB              0.3229627.531188E4 26.00 1   3
-2L3-2.AKDY3NA              0.0489283.271806E4 26.00 1   3
-3L3-2.CKDY3NC              0.0488234.601847E4 26.00 1   3
 0.59747E 00-0.70711E 00-0.41230E 00
 0.53479E 00 0.20486E-12 0.81240E 00
 0.59747E 00 0.70711E 00-0.41230E 00
C
C      KDY series capacitor bank:
C      Detailed series capacitor model with protective gap
C          modified from data from Brent Hughes
C          5L1 Phase A:
  KDY1NAKD1NOA                      1.89-3
  KD1NOAKD1N2A              0.0020.18850
  KD1N2AKD1N1A              3.20001.89-3
  KD1N3AKD1M.AKDY1NAKD1NOA
  KD1NOAKD1M.A              0.01007.54-343960..
  KD1M.A                                  2.4504
  KD1M.AKDY1SAKD1NOAKD1M.A
  KD1S3AKD1M.AKDY1NAKD1NOA
  KD1S2AKD1S1AKD1N2AKD1N1A
  KD1S2AKDY1SAKD1NOAKD1N2A
C          5L1 Phase B:
  KDY1NBKD1NOBKDY1NAKD1NOA
  KD1NOBKD1N2BKD1NOAKD1N2A
  KD1N2BKD1N1BKD1N2AKD1N1A
  KD1N3BKD1M.BKDY1NAKD1NOA
  KD1NOBKD1M.BKD1NOAKD1M.A
  KD1M.B      KD1M.A
  KD1M.BKDY1SBKD1NOAKD1M.A
  KD1S3BKD1M.BKDY1NAKD1NOA
  KD1S2BKD1S1BKD1N2AKD1N1A
  KD1S2BKDY1SBKD1NOAKD1N2A
C          5L1 Phase C:
  KDY1NCKD1NOCKDY1NAKD1NOA
  KD1NOCKD1N2CKD1NOAKD1N2A
  KD1N2CKD1N1CKD1N2AKD1N1A
  KD1N3CKD1M.CKDY1NAKD1NOA

        .........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 24 (cont'd)

```
      KD1NOCKD1M.CKD1NOAKD1M.A
      KD1M.C    KD1M.A
      KD1M.CKDY1SCKD1NOAKD1M.A
      KD1S3CKD1M.CKDY1NAKD1NOA
      KD1S2CKD1S1CKD1N2AKD1N1A
      KD1S2CKDY1SCKD1NOAKD1N2A
C
C          5L2 Phase A:
      KDY2NAKD2NOAKDY1NAKD1NOA
      KD2NOAKD2N2AKD1NOAKD1N2A
      KD2N2AKD2N1AKD1N2AKD1N1A
      KD2N3AKD2M.AKDY1NAKD1NOA
      KD2NOAKD2M.AKD1NOAKD1M.A
      KD2M.A    KD1M.A
      KD2M.AKDY2SAKD1NOAKD1M.A
      KD2S3AKD2M.AKDY1NAKD1NOA
      KD2S2AKD2S1AKD1N2AKD1N1A
      KD2S2AKDY2SAKD1NOAKD1N2A
C          5L2 Phase B:
      KDY2NBKD2NOBKDY1NAKD1NOA
      KD2NOBKD2N2BKD1NOAKD1N2A
      KD2N2BKD2N1BKD1N2AKD1N1A
      KD2N3BKD2M.BKDY1NAKD1NOA
      KD2NOBKD2M.BKD1NOAKD1M.A
      KD2M.B    KD1M.A
      KD2M.BKDY2SBKD1NOAKD1M.A
      KD2S3BKD2M.BKDY1NAKD1NOA
      KD2S2BKD2S1BKD1N2AKD1N1A
      KD2S2BKDY2SBKD1NOAKD1N2A
C          5L2 Phase C:
      KDY2NCKD2NOCKDY1NAKD1NOA
      KD2NOCKD2N2CKD1NOAKD1N2A
      KD2N2CKD2N1CKD1N2AKD1N1A
      KD2N3CKD2M.CKDY1NAKD1NOA
      KD2NOCKD2M.CKD1NOAKD1M.A
      KD2M.C    KD1M.A
      KD2M.CKDY2SCKD1NOAKD1M.A
      KD2S3CKD2M.CKDY1NAKD1NOA
      KD2S2CKD2S1CKD1N2AKD1N1A
      KD2S2CKDY2SCKD1NOAKD1N2A
C
C          5L3 Phase A:
      KDY3NAKD3NOAKDY1NAKD1NOA
      KD3NOAKD3N2AKD1NOAKD1N2A
      KD3N2AKD3N1AKD1N2AKD1N1A
      KD3N3AKD3M.AKDY1NAKD1NOA
      KD3NOAKD3M.A              0.01007.54-343480.
      KD3M.A    KD1M.A
      KD3M.AKDY3SAKD3NOAKD3M.A
      KD3S3AKD3M.AKDY1NAKD1NOA
      KD3S2AKD3S1AKD1N2AKD1N1A
      KD3S2AKDY3SAKD1NOAKD1N2A
C          5L3 Phase B:
      KDY3NBKD3NOBKDY1NAKD1NOA
      KD3NOBKD3N2BKD1NOAKD1N2A
      KD3N2BKD3N1BKD1N2AKD1N1A
```

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.

Fig. 24 (cont'd)

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Listing of SH09012 at 10:46:00 on APR 12, 1986 for CCid=BRWG                                                       Page    6

          KD3N3BKD3M.BKDY1NAKD1NOA
          KD3NOBKD3M.BKD3NOAKD3M.A
          KD3M.B      KD1M.A
          KD3M.BKDY3SBKD3NOAKD3M.A
          KD3S3BKD3M.BKDY1NAKD1NOA
          KD3S2BKD3S1BKD1N2AKD1N1A
          KD3S2BKDY3SBKD1NOAKD1N2A
C               5L3 Phase C:
          KDY3NCKD3NOCKDY1NAKD1NOA
          KD3NOCKD3N2CKD1NOAKD1N2A
          KD3N2CKD3N1CKD1N2AKD1N1A
          KD3N3CKD3M.CKDY1NAKD1NOA
          KD3NOCKD3M.CKD3NOAKD3M.A
          KD3M.C      KD1M.A
          KD3M.CKDY3SCKD3NOAKD3M.A
          KD3S3CKD3M.CKDY1NAKD1NOA
          KD3S2CKD3S1CKD1N2AKD1N1A
          KD3S2CKDY3SCKD1NOAKD1N2A
C
C       5L1, 5L2, and 5L3 from KDY series capacitor bank to second
C           transposition point. Data length adjusted from Brent Hughes
C           case. Untransposed line model.
-1KDY1SBL1-5.B                0.8623947.820893E4 26.00 1   9
-2KDY1SAL1-5.A                0.0484478.891513E4 26.00 1   9
-3KDY1SCL1-5.C                0.0433376.011705E4 26.00 1   9.
-4KDY2SBL2-5.B                0.0395271.181803E4 26.00 1   9
-5KDY2SAL2-5.A                0.0331209.701827E4 26.00 1   9
-6KDY2SCL2-5.C                0.0324202.761838E4 26.00 1   9
-7KDY3SBL3-5.B                0.0477228.751848E4 26.00 1   9
-8KDY3SAL3-5.A                0.0390226.081847E4 26.00 1   9
-9KDY3SCL3-5.C                0.0385219.921849E4 26.00 1   9
 0.35665E 00-0.47171E 00-0.42982E 00-0.44717E 00-0.35065E 00 0.23963E 00
-0.37070E-02 0.31196E 00-0.13818E 00
 0.31678E 00-0.39122E 00-0.23234E 00 0.42209E-02 0.17235E 00-0.22650E 00
-0.41552E-03-0.66235E 00 0.34511E 00
 0.34197E 00-0.33515E 00 0.13433E-01 0.42322E 00 0.40861E 00-0.22179E 00
 0.59782E-02 0.41813E 00-0.33657E 00
 0.34512E 00-0.13700E 00 0.39685E 00 0.39533E 00-0.14213E 00 0.52102E 00
 0.37371E-02 0.85572E-01 0.44310E 00
 0.32004E 00 0.14023E-01 0.45150E 00-0.33083E-01-0.32729E 00-0.58562E-01
-0.67096E-02-0.38795E 00-0.61489E 00
 0.34294E 00 0.16435E 00 0.38142E 00-0.43586E 00 0.32675E-02-0.51105E 00
-0.96139E-01 0.32200E 00 0.37778E 00
 0.32544E 00 0.32838E 00-0.11377E-01-0.31404E 00 0.49650E 00 0.32316E 00
 0.51130E 00-0.87018E-01-0.67666E-01
 0.30399E 00 0.38167E 00-0.24521E 00 0.34340E-01 0.12210E 00 0.17703E 00
-0.76882E 00-0.55044E-01-0.66979E-01
 0.34319E 00 0.46080E 00-0.43738E 00 0.37312E 00-0.40668E 00-0.23920E 00
 0.35910E 00 0.58969E-01 0.57106E-01
C
C       5L1, 5L2, and 5L3 from second transposition point to last 5L3
C           transposition point.
C           Data length-adjusted from Brent Hughes case. Untransposed
C           line model.
C       Transposition effected at sending end of section for all three
C           lines.

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 24 (cont'd)

```
-1L1-5.AL1-6.A              0.8623947.820893E4 33.24 1   9
-2L1-5.CL1-6.C              0.0484478.891513E4 33.24 1   9
-3L1-5.BL1-6.B              0.0433376.011705E4 33.24 1   9
-4L2-5.AL2-6.A              0.0395271.181803E4 33.24 1   9
-5L2-5.CL2-6.C              0.0331209.701827E4 33.24 1   9
-6L2-5.BL2-6.B              0.0324202.761838E4 33.24 1   9
-7L3-5.CL3-6.C              0.0477228.751848E4 33.24 1   9
-8L3-5.BL3-6.B              0.0390226.081847E4 33.24 1   9
-9L3-5.AL3-6.A              0.0385219.921849E4 33.24 1   9
 0.35665E 00-0.47171E 00-0.42982E 00-0.44717E 00-0.35065E 00 0.23963E 00
-0.37070E-02 0.31196E 00-0.13818E 00
 0.31678E 00-0.39122E 00-0.23234E 00 0.42209E-02 0.17235E 00-0.22650E 00
-0.41552E-03-0.66235E 00 0.34511E 00
 0.34197E 00-0.33515E 00 0.13433E-01 0.42322E 00 0.40861E 00-0.22179E 00
 0.59792E-02 0.41813E 00-0.33657E 00
 0.34512E 00-0.13700E 00 0.39685E 00 0.39533E 00-0.14213E 00 0.52102E 00
 0.37371E-02 0.85572E-01 0.44310E 00
 0.32004E 00 0.14023E-01 0.45150E 00-0.33083E-01-0.32729E 00-0.58562E-01
-0.67096E-02-0.38795E 00-0.61489E 00
 0.34294E 00 0.16435E 00 0.38142E 00-0.43586E 00 0.32675E-02-0.51105E 00
-0.96139E-01 0.32200E 00 0.37778E 00
 0.32544E 00 0.32838E 00-0.11377E-01-0.31404E 00 0.49650E 00 0.32316E 00
 0.51130E 00-0.87018E-01-0.67666E-01
 0.30399E 00 0.38167E 00-0.24521E 00 0.34340E-01 0.12210E 00 0.17703E 00
-0.76882E 00-0.55044E-01-0.66979E-01
 0.34318E 00 0.46080E 00-0.43738E 00 0.37312E 00-0.40668E 00-0.23920E 00
 0.35910E 00 0.58969E-01 0.57106E-01
C
C     5L1, 5L2, and 5L3 from last 5L3 transposition point to WSN.
C         Data length adjusted from Brent Hughes case. Untransposed
C          line model. Lengths in miles.
C     Transposition of 5L3 effected at sending end of this section.
-1L1-6.AVT1S.A              0.8623947.820893E4 26.00 1   9
-2L1-6.CVT1S.C              0.0484478.891513E4 26.00 1   9
-3L1-6.BVT1S.B              0.0433376.011705E4 26.00 1   9
-4L2-6.AVT2S.A              0.0395271.181803E4 26.00 1   9
-5L2-6.CVT2S.C              0.0331209.701827E4 26.00 1   9
-6L2-6.BVT2S.B              0.0324202.761838E4 26.00 1   9
-7L3-6.AWSN..A              0.0477228.751848E4 26.00 1   9
-8L3-6.CWSN..C              0.0390226.081847E4 26.00 1   9
-9L3-6.BWSN..B              0.0385219.921849E4 26.00 1   9
 0.35665E 00-0.47171E 00-0.42982E 00-0.44717E 00-0.35065E 00 0.23963E 00
-0.37070E-02 0.31196E 00-0.13818E 00
 0.31678E 00-0.39122E 00-0.23234E 00 0.42209E-02 0.17235E 00-0.22650E 00
-0.41552E-03-0.66235E 00 0.34511E 00
 0.34197E 00-0.33515E 00 0.13433E-01 0.42322E 00 0.40861E 00-0.22178E 00
 0.59792E-02 0.41813E 00-0.33657E 00
 0.34512E 00-0.13700E 00 0.39685E 00 0.39533E 00-0.14213E 00 0.52102E 00
 0.37371E-02 0.85572E-01 0.44310E 00
 0.32004E 00 0.14023E-01 0.45150E 00-0.33083E-01-0.32729E 00-0.58562E-01
-0.67096E-02-0.38795E 00-0.61489E 00
 0.34294E 00 0.16435E 00 0.38142E 00-0.43586E 00 0.32675E-02-0.51105E 00
-0.96139E-01 0.32200E 00 0.37778E 00
 0.32544E 00 0.32838E 00-0.11377E-01-0.31404E 00 0.49650E 00 0.32316E 00
 0.51130E 00-0.87018E-01-0.67666E-01
 0.30399E 00 0.38167E 00-0.24521E 00 0.34340E-01 0.12210E 00 0.17703E 00

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
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Fig. 24 (cont'd)

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Listing of SH09012 at 10:46:00 on APR 12, 1986 for CCid=BRWG                                                              Page  8

-0.76882E 00-0.55044E-01-0.66979E-01
 0.34319E 00 0.46080E 00-0.43738E 00 0.37312E 00-0.40668E 00-0.23920E 00
 0.35910E 00 0.58969E-01 0.57106E-01
C
C     South end 5L1 closing resistors and switch-isolating impedances
C       Also used for current measurement
  VT1S.ACB1S1ACB1N1AVT1N.A
  VT1S.BCB1S1BCB1N1AVT1N.A
  VT1S.CCB1S1CCB1N1AVT1N.A
  CB1S2ACB1S1AGMS..A5L1N.A
  CB1S2BCB1S1BGMS..A5L1N.A
  CB1S2CCB1S1CGMS..A5L1N.A
  WSN..A5L1S.AGMS..A5L1N.A                                                     1
  WSN..B5L1S.BGMS..A5L1N.A                                                     1
  WSN..C5L1S.CGMS..A5L1N.A                                                     1
  VT2S.ACB2S1ACB1N1AVT1N.A
  VT2S.BCB2S1BCB1N1AVT1N.A
  VT2S.CCB2S1CCB1N1AVT1N.A
  CB2S2ACB2S1AGMS..A5L1N.A
  CB2S2BCB2S1BGMS..A5L1N.A
  CB2S2CCB2S1CGMS..A5L1N.A
  WSN..A5L2S.AGMS..A5L1N.A
  WSN..B5L2S.BGMS..A5L1N.A
  WSN..C5L2S.CGMS..A5L1N.A
C
C     5L1 CT is from WSN to 5L1S
C     5L1 CVT is at VT1S
C
C     WSN shunt reactors (2 units):
  WSN..A                    2.5   1020.
  WSN..B                    2.5   1020.
  WSN..C                    2.5   1020.
C
C     5L11 and 5L12 from WSN to first transposition point
C        Data length-adjusted from Brent Hughes case, lengths in
C        miles. Untransposed line model.
-1WSN..AL11-1A              0.5887810.480989E4 69.37 1   6
-2WSN..CL11-1C              0.0413403.201639E4 69.37 1   6
-3WSN..BL11-1B              0.0403287.831800E4 69.37 1   6
-4WSN..AL12-1A              0.0395264.401833E4 69.37 1   6
-5WSN..CL12-1C              0.0395226.801849E4 69.37 1   6
-6WSN..BL12-1B              0.0400232.571847E4 69.37 1   6
 0.42956E 00-0.55248E 00-0.51383E 00 0.43046E 00-0.20804E 00-0.28668E 00
 0.38234E 00-0.39135E 00 0.47696E-03-0.27482E 00 0.50087E 00 0.57596E 00
 0.41140E 00-0.20348E 00 0.48559E 00-0.48519E 00-0.45062E 00-0.29319E 00
 0.41140E 00 0.20348E 00 0.48559E 00 0.48519E 00 0.45062E 00-0.29319E 00
 0.38234E 00 0.39135E 00 0.47696E-03 0.27482E 00-0.50087E 00 0.57596E 00
 0.42956E 00 0.55248E 00-0.51383E 00-0.43046E 00 0.20804E 00-0.28668E 00
C
C     5L11 and 5L12 from first transposition point to MLS series
C        capacitor bank. Data length-adjusted from Brent Hughes
C        case, lengths in miles. Untransposed line model.
C     Transposition effected at sending end of this section.
-1L11-1CMLS1NC              0.5887810.480989E4 33.24 1   6
-2L11-1BMLS1NB              0.0413403.201639E4 33.24 1   6
-3L11-1AMLS1NA              0.0403287.831800E4 33.24 1   6

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 24 (cont'd)

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-4L12-1CMLS2NC               0.0395264.401833E4 33.24 1   6
-5L12-1BMLS2NB               0.0395226.801849E4 33.24 1   6
-6L12-1AMLS2NA               0.0400232.571847E4 33.24 1   6
 0.42956E 00-0.55248E 00-0.51383E 00 0.43046E 00-0.20804E 00-0.28668E 00
 0.38234E 00-0.39135E 00 0.47696E-03-0.27482E 00 0.50087E 00 0.57596E 00
 0.41140E 00-0.20348E 00 0.48559E 00-0.48519E 00-0.45062E 00-0.29319E 00
 0.41140E 00 0.20348E 00 0.48559E 00 0.48519E 00 0.45062E 00-0.29319E 00
 0.38234E 00 0.39135E 00 0.47696E-03 0.27482E 00-0.50087E 00 0.57596E 00
 0.42956E 00 0.55248E 00-0.51383E 00-0.43046E 00 0.20804E 00-0.28668E 00
C
C     MLS series capacitor bank
  MLS1NAMLS1SA                                18518.
  MLS1NBMLS1SBMLS1NAMLS1SA
  MLS1NCMLS1SCMLS1NAMLS1SA
  MLS2NAMLS2SAMLS1NAMLS1SA
  MLS2NBMLS2SBMLS1NAMLS1SA
  MLS2NCMLS2SCMLS1NAMLS1SA
C
C     5L11 and 5L12 from MLS series capacitor bank to second
C         transposition point. Data length-adjusted from Brent
C         Hughes case, lengths in miles. Untransposed line model.
-1MLS1SCL11-4C               0.5887810.480989E4 33.24 1   6
-2MLS1SBL11-4B               0.0413403.201639E4 33.24 1   6
-3MLS1SAL11-4A               0.0403287.831800E4 33.24 1   6
-4MLS2SCL12-4C               0.0395264.401833E4 33.24 1   6
-5MLS2SBL12-4B               0.0395226.801849E4 33.24 1   6
-6MLS2SAL12-4A               0.0400232.571847E4 33.24 1   6
 0.42956E 00-0.55248E 00-0.51383E 00 0.43046E 00-0.20804E 00-0.28668E 00
 0.38234E 00-0.39135E 00 0.47696E-03-0.27482E 00 0.50087E 00 0.57596E 00
 0.41140E 00-0.20348E 00 0.48559E 00-0.48519E 00-0.45062E 00-0.29319E 00
 0.41140E 00 0.20348E 00 0.48559E 00 0.48519E 00 0.45062E 00-0.29319E 00
 0.38234E 00 0.39135E 00 0.47696E-03 0.27482E 00-0.50087E 00 0.57596E 00
 0.42956E 00 0.55248E 00-0.51383E 00-0.43046E 00 0.20804E 00-0.28668E 00
C
C     5L11 and 5L12 from second transposition point to KLY. Data from
C         Brent Hughes case, lengths in miles. Untransposed line model.
C     Transpositions effected at sending end of this section.
-1L11-4BKLY..B               0.5887810.480989E4 69.37 1   6
-2L11-4AKLY..A               0.0413403.201639E4 69.37 1   6
-3L11-4CKLY..C               0.0403287.831800E4 69.37 1   6
-4L12-4BKLY..B               0.0395264.401833E4 69.37 1   6
-5L12-4AKLY..A               0.0395226.801849E4 69.37 1   6
-6L12-4CKLY..C               0.0400232.571847E4 69.37 1   6
 0.42956E 00-0.55248E 00-0.51383E 00 0.43046E 00-0.20804E 00-0.28668E 00
 0.38234E 00-0.39135E 00 0.47696E-03-0.27482E 00 0.50087E 00 0.57596E 00
 0.41140E 00-0.20348E 00 0.48559E 00-0.48519E 00-0.45062E 00-0.29319E 00
 0.41140E 00 0.20348E 00 0.48559E 00 0.48519E 00 0.45062E 00-0.29319E 00
 0.38234E 00 0.39135E 00 0.47696E-03 0.27482E 00-0.50087E 00 0.57596E 00
 0.42956E 00 0.55248E 00-0.51383E 00-0.43046E 00 0.20804E 00-0.28668E 00
C     end of Peace River system
C
C     North Coast system follows:
C         Original data
C
C     WSN to GLN as untransposed distributed line model (5L61)
C     (Lengths in Km)

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
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Fig. 24 (cont'd)

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Listing of SH09012 at 10:46:00 on APR 12, 1986 for CCid=BRWG                                          Page   10

-1WSN..AL61-1A                .197851.49633.216658.127      3
-2WSN..CL61-1C               2.28-2.364904.635558.127      3
-3WSN..BL61-1B               2.28-2.295025.460658.127      3
 5.98060E-01-7.07107E-01-4.11569E-01
 5.33509E-01 5.60358E-17 8.13152E-01
 5.98060E-01 7.07107E-01-4.11569E-01
-1L61-1BL61-2BWSN..AL61-1A
-2L61-1AL61-2A
-3L61-1CL61-2C
-1L61-2CGLN..CWSN..AL61-1A
-2L61-2BGLN..B
-3L61-2AGLN..A
C
C      GLN Thevenin equivalent
C         (GLN internal voltage is zero, so Thevenin impedance
C          is grounded)
51       GLN..A                 -228.6998596       107075.4375
52       GLN..B                  114.4370880      -53488.20703
                                -228.6998596       107075.4375
53       GLN..C                  114.4370880      -53488.20703
                                 114.4370880      -53488.20703
                                -228.6998596       107075.4375
C
C      GLN shunt reactors (1 unit)
  GLN..A                            2005.4
  GLN..B                            2005.4
  GLN..C                            2005.4
C
C      GLN to TKW as untransposed distributed line model (5L62)
C         (lengths in Km)
-1GLN..CL62-1C                .197851.49633.216643.847      3
-2GLN..BL62-1B               2.28-2.364904.635543.847      3
-3GLN..AL62-1A               2.28-2.295025.460643.847      3
 5.98060E-01-7.07107E-01-4.11569E-01
 5.33509E-01 5.60358E-17 8.13152E-01
 5.98060E-01 7.07107E-01-4.11569E-01
-1L62-1AL62-2AGLN..CL62-1C
-2L62-1CL62-2C
-3L62-1BL62-2B
-1L62-2BTKW..BGLN..CL62-1C
-2L62-2ATKW..A
-3L62-2CTKW..C
C
C      TKW Thevenin equivalent
C         (TKW internal voltage is zero, so Thevenin impedance
C          is grounded)
51       TKW..A                  16666666.00       34.91661072
52       TKW..B                 -8333333.000       34.91661072
                                 16666666.00       34.91661072
53       TKW..C                 -8333333.000       34.91661072
                                -8333333.000       34.91661072
                                 16666666.00       34.91661072
C
C      TKW to SKA as untransposed distributed line model (5L63)
C         (lengths in Km)
-1TKW..BL63-1B                .197851.49633.216647.657      3

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 24 (cont'd)

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-2TKW..AL63-1A             2.28-2.364904.635547.657    3
-3TKW..CL63-1C             2.28-2.295025.460647.657    3
 5.98060E-01-7.07107E-01-4.11569E-01
 5.33509E-01 5.60358E-17 8.13152E-01
 5.98060E-01 7.07107E-01-4.11569E-01
-1L63-1CL63-2CTKW..BL63-1B
-2L63-1BL63-2B
-3L63-1AL63-2A
-1L63-2ASKA..ATKW..BL63-1B
-2L63-2CSKA..C
-3L63-2BSKA..B
C
C      SKA Thevenin equivalent impedance
C         (SKA-E is SKA internal voltage node)
 1SKA-EASKA..A             7.9583165.03
 2SKA-EBSKA..B             -2.742-36.33       7.9583165.03
 3SKA-ECSKA..C             -2.742-36.33       -2.742-36.33       7.9583165.03
C      end of North Coast system
C
C      Kelly Lake south system--remainder of B.C. Hydro network
C         Data from Jack Sawada case. (CRK gap-flashing removed)
C
C      KLY Thevenin equivalent source
C         (KLY-E is internal voltage node)
C=================================
C      WSN-KLY coupled Thevenin equivalent impedance
C         (KLY-E is KLY internal voltage node,
C          WSN-E is WSN internal voltage node.)
51WSN-EAWSN..A               11.70095158       217.7675171
52WSN-EBWSN..B              -5.362372398      -70.73513794
                             11.70091248       217.7675171
53WSN-ECWSN..C              -5.425845146      -70.72546387
                            -5.362503052      -70.73533630
                             11.70127869       217.7674408
54KLY-EAKLY..A              0.6675326228       26.30413818
                           -0.3888940811      -13.06832600
                           -0.3319950104      -13.07547474
                             8.224038124       132.3419342
55KLY-EBKLY..B             -0.3317694664      -13.07512856
                            0.6673421860       26.30416870
                           -0.3887786865      -13.06860542
                            -2.418684006      -10.85663509
                             8.223999023       132.3419495
56KLY-ECKLY..C             -0.3888553977      -13.06842995
                           -0.3320865631      -13.07566166
                            0.6679344177       26.30412292
                            -2.457177162      -10.84912014
                            -2.418750763      -10.85673428
                             8.223999023       132.3419189
C==================================================
C
C      KLY reactors (4 units)
  KLY..A                   1.25  510.0
  KLY..B                   1.25  510.0
  KLY..C                   1.25  510.0
C
.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
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Fig. 24 (cont'd)

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Listing of SH09012 at 10:46:00 on APR 12, 1986 for CCId=BRWG                                                    Page  12

C      KLY to CRK series capacitor bank. Untransposed line model (5L42)
-1KLY..BL42-2B                0.3153622.981174E4 57.50 1   3
-2KLY..AL42-2A                0.0405280.491802E4 57.50 1   3
-3KLY..CL42-2C                0.0404232.181846E4 57.50 1   3
 0.59717E 00-0.70711E 00-0.41249E 00
 0.53551E 00-0.21620E-12 0.81222E 00
 0.59717E 00 0.70711E 00-0.41249E 00
-1L42-2ACRK..A                0.3153622.981174E4 14.80 1   3
-2L42-2CCRK..C                0.0405280.491802E4 14.80 1   3
-3L42-2BCRK..B                0.0404232.181846E4 14.80 1   3
 0.59717E 00-0.70711E 00-0.41249E 00
 0.53551E 00-0.21620E-12 0.81222E 00
 0.59717E 00 0.70711E 00-0.41249E 00
C
C      CRK series capacitor bank
  CRK..ACRK.CA                               26518.
  CRK..BCRK.CBCRK..ACRK.CA
  CRK..CCRK.CCCRK..ACRK.CA
C
C      CRK series capacitor bank to CKY (5L42)
-1CRK.CACKY..A                0.3153622.981174E4 51.70 1   3
-2CRK.CCCKY..C                0.0405280.491802E4 51.70 1   3
-3CRK.CBCKY..B                0.0404232.181846E4 51.70 1   3
 0.59717E 00-0.70711E 00-0.41249E 00
 0.53551E 00-0.21620E-12 0.81222E 00
 0.59717E 00 0.70711E 00-0.41249E 00
C
C      CKY to MSA (5L30) (untransposed line model)
-1CKY..CL30-1C                0.3112623.421183E4 18.64 1   3
-2CKY..BL30-1B                0.0370284.261803E4 18.64 1   3
-3CKY..AL30-1A                0.0369235.981846E4 18.64 1   3
 0.59666E 00-0.70711E 00-0.41260E 00
 0.53664E 00-0.63310E-12 0.81211E 00
 0.59666E 00 0.70711E 00-0.41260E 00
-1L30-1AL30-2A                0.3112623.421183E4 12.02 1   3
-2L30-1CL30-2C                0.0370284.261803E4 12.02 1   3
-3L30-1BL30-2B                0.0369235.981846E4 12.02 1   3
 0.59666E 00-0.70711E 00-0.41260E 00
 0.53664E 00-0.63310E-12 0.81211E 00
 0.59666E 00 0.70711E 00-0.41260E 00
-1L30-2BMSA..B                0.3112623.421183E4 18.90 1   3
-2L30-2AMSA..A                0.0370284.261803E4 18.90 1   3
-3L30-2CMSA..C                0.0369235.981846E4 18.90 1   3
 0.59666E 00-0.70711E 00-0.41260E 00
 0.53664E 00-0.63310E-12 0.81211E 00
 0.59666E 00 0.70711E 00-0.41260E 00
C
C      MSA Thevenin equivalent
C         (MSA-E is internal voltage node)
 1MSA-EAMSA..A                7.241783.442
 2MSA-EBMSA..B               -1.358-6.683      7.241783.442
 3MSA-ECMSA..C               -1.356-6.683     -1.358-6.683      7.241783.442
C
C      MSA shunt reactors (1 unit)
  MSA..A                      5.   2040.0
  MSA..B                      5.   2040.

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 24 (cont'd)

```
  MSA..C                       5.   2040.
C
C     CKY to MDN (5L45)
-1CKY..CMDN..C               0.3153622.981174E4 46.00 1   3
-2CKY..BMDN..B               0.0405280.491802E4 46.00 1   3
-3CKY..AMDN..A               0.0404232.181846E4 46.00 1   3
 0.59717E 00-0.70711E 00-0.41249E 00
 0.53551E 00-0.21620E-12 0.81222E 00
 0.59717E 00 0.70711E 00-0.41249E 00
C
C     MDN Thevenin source:
C         (MDN-E is internal voltage node)
 1MDN-EAMDN..A               2.558349.283
 2MDN-EBMDN..B               .13333-2.742      2.558349.283
 3MDN-ECMDN..C               .13333-2.742      .13333-2.742      2.558349.283
C
C     MDN to ING (5L44)
-1MDN..CING..C               0.3153622.981174E4 12.16 1   3
-2MDN..BING..B               0.0405280.491802E4 12.16 1   3
-3MDN..AING..A               0.0404232.181846E4 12.16 1   3
 0.59717E 00-0.70711E 00-0.41249E 00
 0.53551E 00-0.21620E-12 0.81222E 00
 0.59717E 00 0.70711E 00-0.41249E 00
C
C     ING Thevenin equivalent source
C         (ING-E is internal voltage node)
 1ING-EAING..A               5.350052.250
 2ING-EBING..B               -1.825-10.83      5.350052.250
 3ING-ECING..C               -1.825-10.83      -1.825-10.83      5.350052.250
C
C     KLY to CHP series capacitor bank
 1KLY..BL41-2B                 8.68 67.31464.91
 2KLY..AL41-2A                 6.05 34.26-85.40  8.68 67.31479.17
 3KLY..CL41-2C                 6.04 28.73-25.91  6.05 34.26-85.40  8.68 67.31464.91
 1L41-2ACHP.3A                 4.37 33.86233.87
 2L41-2CCHP.3C                 3.04 17.23-42.96  4.37 33.86241.04
 3L41-2BCHP.3B                 3.04 14.45-13.04  3.04 17.23-42.96  4.37 33.86233.87
C
C     CHP series capacitor bank
  CHP.3ACHP.4A                                  19531.
  CHP.3BCHP.4BCHP.3ACHP.4A
  CHP.3CCHP.4CCHP.3ACHP.4A
C
C     5L41 from CHP series capacitor bank to junction of 5L81
 1CHP.4AL41-5A                 4.37 33.86233.87
 2CHP.4CL41-5C                 3.04 17.23-42.96  4.37 33.86241.04
 3CHP.4BL41-5B                 3.04 14.45-13.04  3.04 17.23-42.96  4.37 33.86233.87
C
C     junction of 5L41 from CHP to ING (with parallel 5L81)
 1L81-5CING..C                 8.32 65.26465.64
 2L81-5BING..B                 5.91 33.97-84.16  8.32 65.26480.29
 3L81-5AING..A                 5.90 28.59-23.64  5.91 33.97-82.37  8.32 65.26471.59
 4L41-5CING..C                 5.88 23.93 -8.50  5.88 26.40-15.72  5.89 30.05-46.22
                               8.44 65.47458.47
 5L41-5BING..B                 5.86 21.90 -4.55  5.87 23.74 -6.73  5.88 26.14-14.37
                               5.88 33.32-80.94  8.44 65.47466.80

........1........2........3........4........5........6........7........8........9........0........1........2
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Fig. 24 (cont'd)

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 6L41-5AING..A                5.85 20.30 -3.33  5.86 21.76 -4.26  5.87 23.55 -7.27
                              5.87 27.94-24.05  5.88 33.32-82.66  8.44 65.47452.42
C
C     5L81 from junction with 5L41 to junction with 5L82
 1L81-5AL81-3A                2.88 21.41152.69
 2L81-5CL81-3C                1.94 11.15-27.78  2.88 21.41157.32
 3L81-5BL81-3B                1.94  9.38 -8.19  1.94 11.15-27.78  2.88 21.41152.69
C
C     5L82 from MDN to junction with 5L81
 1MDN..CL82-5C                8.22 61.18436.26
 2MDN..BL82-5B                5.54 31.84-79.37  8.22 61.18449.48
 3MDN..AL82-5A                5.53 26.80-23.40  5.54 31.84-79.37  8.22 61.18436.26
 1L82-5AL82-3A                2.33 17.33123.61
 2L82-5CL82-3C                1.57  9.02-22.49  2.33 17.33127.35
 3L82-5BL82-3B                1.57  7.59 -6.63  1.57  9.02-22.49  2.33 17.33123.61
C
C     5L81 and 5L82 from junction to NIC
 1L82-3AL82-2A                4.38 32.63232.71
 2L82-3CL82-2C                2.95 16.98-42.27  4.38 32.63239.80
 3L82-3BL82-2B                2.95 14.29-12.37  2.95 16.98-42.17  4.38 32.63232.99
 4L81-3AL81-2A                2.93 10.34 -2.10  2.94 11.11 -3.08  2.95 12.08 -6.64
                              4.38 32.63232.99
 5L81-3CL81-2C                2.92  8.70 -1.26  2.93 10.34 -1.66  2.94 11.11 -3.08
                              2.95 16.98-42.17  4.38 32.63239.80
 6L81-3BL81-2B                2.92  9.15 -1.03  2.92  9.70 -1.26  2.93 10.34 -2.10
                              2.95 14.29-12.37  2.95 16.98-42.27  4.38 32.63232.71
 1L82-2BNIC..B                6.50 50.98363.62
 2L82-2ANIC..A                4.61 26.54-66.05  6.50 50.98374.68
 3L82-2CNIC..C                4.61 22.34-19.32  4.61 26.54-65.90  6.50 50.98364.05
 4L81-2BNIC..B                4.58 16.16 -3.28  4.59 17.36 -4.81  4.60 18.87-10.38
                              6.50 50.98364.05
 5L81-2ANIC..A                4.57 15.16 -1.97  4.58 16.16 -2.59  4.59 17.36 -4.81
                              4.61 26.54-65.90  6.50 50.98374.68
 6L81-2CNIC..C                4.56 14.30 -1.61  4.57 15.16 -1.97  4.58 16.16 -3.28
                              4.61 22.34-19.32  4.61 26.54-66.05  6.50 50.98363.62
C
C     NIC thevenin equivalent source
C         (NIC-E is internal voltage node)
 1NIC-EANIC..A              47.02 426.18
 2NIC-EBNIC..B              -22.99-165.1      47.02 426.18
 3NIC-ECNIC..C              -22.99-165.1      -22.99-165.1      47.02 426.18
C
C     NIC shunt reactors (5 units)
C     (values repeated because of two parallel branches)
  NIC..A                    1.     408.30
  NIC..B                    1.     408.30
  NIC..C                    1.     408.30
C
C     5L87 NIC to KLY
C         Data from Jack Sawada. Continuously-transposed distributed-
C                parameter line model. (lengths in KM)
-1NIC..AKLY..A              0.205 1.350 3.1400 146.0
-2NIC..BKLY..B              0.028 0.322 5.0850 146.0
-3NIC..CKLY..C
C
C     5L71 and 5L72 from NIC to MCA

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
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Fig. 24 (cont'd)

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Listing of SH09012 at 10:46:00 on APR 12, 1986 for CCid=BRWG                                              Page  15

        1NIC..BADL..B               8.06 63.22450.88
        2NIC..AADL..A               5.72 32.91-81.91  8.06 63.22464.61
        3NIC..CADL..C               5.72 27.70-23.96  5.72 32.91-81.71  8.06 63.22451.42
        4NIC..BL71-5B               5.68 20.04 -4.06  5.69 21.53 -5.96  5.71 23.40-12.87
                                    8.06 63.22451.42
        5NIC..AL71-5A               5.67 18.79 -2.44  5.68 20.04 -3.21  5.69 21.53 -5.96
                                    5.72 32.91-81.71  8.06 63.22464.61
        6NIC..CL71-5C               5.65 17.73 -2.00  5.67 18.79 -2.44  5.68 20.04 -4.06
                                    5.72 27.70-23.96  5.72 32.91-81.91  8.06 63.22450.88
        1ADL..AL72-2A               7.93 62.20443.61
        2ADL..CL72-2C               5.63 32.37-80.58  7.93 62.20457.12
        3ADL..BL72-2B               5.62 27.25-23.57  5.63 32.37-80.39  7.93 62.20444.14
        4L71-5AL71-2A               5.59 19.71 -4.00  5.60 21.18 -5.86  5.61 23.02-12.66
                                    7.93 62.20444.14
        5L71-5CL71-2C               5.57 18.49 -2.40  5.59 19.71 -3.16  5.60 21.18 -5.86
                                    5.63 32.37-80.39  7.93 62.20457.12
        6L71-5BL71-2B               5.56 17.44 -1.97  5.57 18.49 -2.40  5.59 19.71 -4.00
                                    5.62 27.25-23.57  5.63 32.37-80.58  7.93 62.20443.61
        1L72-2CMCA..C               6.85 50.98363.62
        2L72-2BMCA..B               4.62 26.54-66.05  6.85 50.98374.68
        3L72-2AMCA..A               4.61 22.34-19.32  4.62 26.54-65.90  6.85 50.98364.05
        4L71-2CMCA..C               4.58 16.16 -3.28  4.59 17.36 -4.81  4.60 18.87-10.38
                                    6.85 50.98364.05
        5L71-2BMCA..B               4.57 15.16 -1.97  4.58 16.16 -2.59  4.59 17.36 -4.81
                                    4.62 26.54-65.90  6.85 50.98374.68
        6L71-2AMCA..A               4.56 14.30 -1.61  4.57 15.16 -1.97  4.58 16.16 -3.28
                                    4.61 22.34-19.32  4.62 26.54-66.05  6.85 50.98363.62
       C
       C     MCA Thevenin equivalent
       C     (MCA-E is internal voltage node)
        1MCA-EAMCA..A                   26.4
        2MCA-EBMCA..B                   -4.29             26.4
        3MCA-ECMCA..C                   -4.29             -4.29             26.4
       C
       C     MCA shunt reactors (2 units)
         MCA..A                         1020.1
         MCA..B                         1020.1
         MCA..C                         1020.1
       C
       C     NIC to ACK (5L76 and 5L79)
        1NIC..BL76-2B               3.28 24.48171.09
        2NIC..AL76-2A               2.21 12.70-33.17  3.28 24.48177.02
        3NIC..CL76-2C               2.20 10.68-10.05  2.21 12.70-32.97  3.28 24.48171.66
        4NIC..BL79-2B               2.19  8.12 -2.16  2.20  8.80 -3.43  2.20  9.68 -8.23
                                    3.28 24.48171.66
        5NIC..AL79-2A               2.19  7.57 -1.25  2.19  8.12 -1.73  2.20  8.80 -3.43
                                    2.21 12.70-32.97  3.28 24.48177.02
        6NIC..CL79-2C               2.18  7.11 -1.00  2.19  7.57 -1.25  2.19  8.12 -2.16
                                    2.20 10.68-10.05  2.21 12.70-33.17  3.28 24.48171.09
        1L76-2CL76-1C               3.28 24.48171.09
        2L76-2BL76-1B               2.21 12.70-33.17  3.28 24.48177.02
        3L76-2AL76-1A               2.20 10.68-10.05  2.21 12.70-32.97  3.28 24.48171.66
        4L79-2CL79-1C               2.19  8.12 -2.16  2.20  8.80 -3.43  2.20  9.68 -8.23
                                    3.28 24.48171.66
        5L79-2BL79-1B               2.19  7.57 -1.25  2.19  8:12 -1.73  2.20  8.80 -3.43
                                    2.21 12.70-32.97  3.28 24.48177.02

       .........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
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Fig. 24 (cont'd)

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 6L79-2AL79-1A              2.18  7.11 -1.00  2.19  7.57 -1.25  2.19  8.12 -2.16
                            2.20 10.68-10.05  2.21 12.70-33.17  3.28 24.48171.09
 1L76-1AACK..A              3.28 24.48171.09
 2L76-1CACK..C              2.21 12.70-33.17  3.28 24.48177.02
 3L76-1BACK..B              2.20 10.68-10.05  2.21 12.70-32.97  3.28 24.48171.66
 4L79-1AACK..A              2.19  8.12 -2.16  2.20  8.80 -3.43  2.20  9.68 -8.23
                            3.28 24.48171.66
 5L79-1CACK..C              2.19  7.57 -1.25  2.19  8.12 -1.73  2.20  8.80 -3.43
                            2.21 12.70-32.97  3.28 24.48177.02
 6L79-1BACK..B              2.18  7.11 -1.00  2.19  7.57 -1.25  2.19  8.12 -2.16
                            2.20 10.68-10.05  2.21 12.70-33.17  3.28 24.48171.09
C
C     ACK Thevenin equivalent
C     (ACK-E is internal voltage node)
 1ACK-EAACK..A            62.25 328.27
 2ACK-EBACK..B            -29.78-111.8      62.25 328.27
 3ACK-ECACK..C            -29.78-111.8      -29.78-111.8      62.25 328.27
C
C     ACK shunt reactors (1 unit)
C     (repeat values because of two parallel branches)
  ACK..A                  1.     2040.0
  ACK..B                  1.     2040.0
  ACK..C                  1.     2040.0
C
C     ACK to REV (5L77 and 5L75)
 1ACK..AREV..A             6.58053.751348.30
 2ACK..BREV..B             4.71526.252-70.74 6.58053.750357.86
 3ACK..CREV..C             4.70921.840-23.78 4.71526.252-71.61 6.58053.751345.34
 4ACK..AREV..A             4.71122.524-40.77 4.70319.708-15.52 4.69217.764 -8.58
                           6.58053.752330.67
 5ACK..BREV..B             4.67916.294 -5.41 4.69217.783 -9.07 4.70319.734-21.24
                           4.64814.275 -3.42 6.58053.751343.78
 6ACK..CREV..C             4.66315.105 -3.52 4.67916.310 -5.15 4.69317.803-10.18
                           4.62813.392 -2.55 4.71526.330-77.95 6.58053.751342.15
C
C     REV Thevenin equivalent
C        (REV-E is internal voltage node)
 1REV-EAREV..A            1.67-243.333
 2REV-EBREV..B            -8.3-3-11.42      1.67-243.333
 3REV-ECREV..C            -8.3-3-11.42      -8.3-3-11.42      1.67-243.333
C
C     5L91 from ACK to SEL
 1ACK..AL91-1A              6.42 47.95334.95
 2ACK..CL91-1C              4.32 24.86-65.12  6.42 47.94346.43
 3ACK..BL91-1B              4.32 20.91-20.05  4.32 24.86-65.12  6.42 47.95334.95
 1L91-1BL91-2B              6.42 47.95334.95
 2L91-1AL91-2A              4.32 24.86-65.12  6.42 47.94346.43
 3L91-1CL91-2C              4.32 20.91-20.05  4.32 24.86-65.12  6.42 47.95334.95
 1L91-2CSEL..C              6.42 47.95334.95
 2L91-2BSEL..B              4.32 24.86-65.12  6.42 47.94346.43
 3L91-2ASEL..A              4.32 20.91-20.05  4.32 24.86-65.12  6.42 47.95334.95
C
C     SEL Thevenin equivalent:
C        (SEL-E is internal voltage node)
 1SEL-EASEL..A            2.008355.442
 2SEL-EBSEL..B            8.33-2-4.083      2.008355.442

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
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Fig. 24 (cont'd)

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 3SEL-ECSEL..C          8.33-2-4.083     8.33-2-4.083     2.008355.442
C
C     SEL shunt reactors (1 unit)
  SEL..A                           2040.1
  SEL..B                           2040.1
  SEL..C                           2040.1
C
C     5L98 NIC to SEL
C        Data from Jack Sawada, continuously-transposed distributed-
C             parameter line model (lengths in KM?)
-1SEL..ANIC..A           .2054 1.249 3.14   302.
-2SEL..BNIC..B           .0277 0.323 5.08   302.
-3SEL..CNIC..C
C
C     end of BC Hydro system
C
C     BC Hydro intertie to Bonneville Power Administration follows:
C
C     ING to CUS (5L51 and 5L52) (untransposed line model)
C        (twin circuits, modelled uncoupled)
-1ING..ACUS..A          0.3115627.611180E4 22.50 1   3
-2ING..BCUS..B          0.0370279.941805E4 22.50 1   3
-3ING..CCUS..C          0.0369231.231846E4 22.50 1   3
 0.59815E 00-0.70711E 00-0.41217E 00
 0.53332E 00-0.13355E-08 0.81254E 00
 0.59815E 00 0.70711E 00-0.41217E 00
-1ING..ACUS..AING..ACUS..A
-2ING..BCUS..B
-3ING..CCUS..C
C
C     CUSTER to MONROE (untransposed line model)
C        (twin circuits, modelled uncoupled)
-1CUS..AMON..A          0.2954687.901243E4 86.00 1   3
-2CUS..BMON..B          0.0272263.051831E4 86.00 1   3
-3CUS..CMON..C          0.0274254.461843E4 86.00 1   3
 0.63026E 00-0.70711E 00-0.39035E 00
 0.45336E 00 0.66850E-05 0.83382E 00
 0.63026E 00 0.70711E 00-0.39035E 00
-1CUS..AMON..ACUS..AMON..A
-2CUS..BMON..B
-3CUS..CMON..C
C
C     MON Thevenin equivalent source
C        (MON-E is internal voltage node)
 1MON-EAMON..A          2.030 52.13
 2MON-EBMON..B          1.660 4.380      2.030 52.13
 3MON-ECMON..C          1.660 4.380      1.660 4.380      2.030 52.13
C
C     end of network

  FAULT1FAULT23.780583-31.00000000
  5L1N.ACB1N1A-1.      1.0         30.0
  5L1N.BCB1N1B-1.      1.0         30.0
  5L1N.CCB1N1C-1.      1.0         30.0
  CB1N2AVT1N.A-1.      1.0         30.0
  CB1N2BVT1N.B-1.      1.0         30.0

........1.......2.......3.......4.......5.......6.......7.......8.......9.......0.......1.......2.
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Fig. 24 (cont'd)

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Listing of SH09012 at 10:46:00 on APR 12, 1986 for CCid=BRWG                                   Page   18

    952        CB1N2CVT1N.C-1.       1.0          30.0
    953        5L1S.ACB1S1A-1.       1.0          30.0
    954        5L1S.BCB1S1B-1.       1.0          30.0
    955        5L1S.CCB1S1C-1.       1.0          30.0
    956        CB1S2AVT1S.A-1.       1.0          30.0
    957        CB1S2BVT1S.B-1.       1.0          30.0
    958        CB1S2CVT1S.C-1.       1.0          30.0
    959        5L2N.ACB2N1A-1.       1.0          30.0
    960        5L2N.BCB2N1B-1.       1.0          30.0
    961        5L2N.CCB2N1C-1.       1.0          30.0
    962        CB2N2AVT2N.A-1.       1.0          30.0
    963        CB2N2BVT2N.B-1.       1.0          30.0
    964        CB2N2CVT2N.C-1.       1.0          30.0
    965        CB2S1A5L2S.A-1.       1.0          30.0
    966        CB2S1B5L2S.B-1.       1.0          30.0
    967        CB2S1C5L2S.C-1.       1.0          30.0
    968        CB2S2AVT2S.A-1.       1.0          30.0
    969        CB2S2BVT2S.B-1.       1.0          30.0
    970        CB2S2CVT2S.C-1.       1.0          30.0
    971        KD1NOAKD1N1AO.        .083     30.0       10000.
    972        KD1N2AKD1N3AO.        .083     30.0       190890.
    973        KDY1SAKD1S1AO.        .083     30.0       10000.
    974        KD1S2AKD1S3AO.        .083     30.0       190890.
    975        KD1NOBKD1N1BO.        .083     30.0       10000.
    976        KD1N2BKD1N3BO.        .083     30.0       190890.
    977        KDY1SBKD1S1BO.        .083     30.0       10000.
    978        KD1S2BKD1S3BO.        .083     30.0       190890.
    979        KD1NOCKD1N1CO.        .083     30.0       10000.
    980        KD1N2CKD1N3CO.        .083     30.0       190890.
    981        KDY1SCKD1S1CO.        .083     30.0       10000.
    982        KD1S2CKD1S3CO.        .083     30.0       190890.
    983        KD2NOAKD2N1AO.        .083     30.0       10000.
    984        KD2N2AKD2N3AO.        .083     30.0       190890.
    985        KDY2SAKD2S1AO.        .083     30.0       10000.
    986        KD2S2AKD2S3AO.        .083     30.0       190890.
    987        KD2NOBKD2N1BO.        .083     30.0       10000.
    988        KD2N2BKD2N3BO.        .083     30.0       190890.
    989        KDY2SBKD2S1BO.        .083     30.0       10000.
    990        KD2S2BKD2S3BO.        .083     30.0       190890.
    991        KD2NOCKD2N1CO.        .083     30.0       10000.
    992        KD2N2CKD2N3CO.        .083     30.0       190890.
    993        KDY2SCKD2S1CO.        .083     30.0       10000.
    994        KD2S2CKD2S3CO.        .083     30.0       190890.
    995        KD3NOAKD3N1AO.        .083     30.0       10000.
    996        KD3N2AKD3N3AO.        .083     30.0       192420.
    997        KDY3SAKD3S1AO.        .083     30.0       10000.
    998        KD3S2AKD3S3AO.        .083     30.0       192420.
    999        KD3NOBKD3N1BO.        .083     30.0       10000.
   1000        KD3N2BKD3N3BO.        .083     30.0       192420.
   1001        KDY3SBKD3S1BO.        .083     30.0       10000.
   1002        KD3S2BKD3S3BO.        .083     30.0       192420.
   1003        KD3NOCKD3N1CO.        .083     30.0       10000.
   1004        KD3N2CKD3N3CO.        .083     30.0       192420.
   1005        KDY3SCKD3S1CO.        .083     30.0       10000.
   1006        KD3S2CKD3S3CO.        .083     30.0       192420.
   1007

          .........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
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Fig. 24 (cont'd)

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Listing of SHO9012 at 10:46:00 on APR 12, 1986 for CCid=BRWG                                          Page  19

          14GMS-EA 0425767.790   60.      46.201000                       -1.        1.
          14GMS-EB 0425767.790   60.     -73.799000                       -1.        1.
          14GMS-EC 0425767.790   60.     166.20100                        -1.        1.
          14PCN-EA 0425815.370   60.      49.345000                       -1.        1.
          14PCN-EB 0425815.370   60.     -70.655000                       -1.        1.
          14PCN-EC 0425815.370   60.     169.34500                        -1.        1.
          14KLY-EA 0396003.260   60.      2.3866000                       -1.        1.
          14KLY-EB 0396003.260   60.    -117.61340                        -1.        1.
          14KLY-EC 0396003.260   60.     122.38660                        -1.        1.
          14WSN-EA 0468378.670   60.     - 1.351100                       -1.        1.
          14WSN-EB 0468378.670   60.    -121.35110                        -1.        1.
          14WSN-EC 0468378.670   60.     118.64890                        -1.        1.
          14SKA-EA 0403532.450   60.      21.140000                       -1.        1.
          14SKA-EB 0403532.450   60.     -98.860000                       -1.        1.
          14SKA-EC 0403532.450   60.     141.14000                        -1.        1.
          14SEL-EA 0430136.720   60.      11.854000                       -1.        1.
          14SEL-EB 0430136.720   60.    -108.14600                        -1.        1.
          14SEL-EC 0430136.720   60.     131.85400                        -1.        1.
          14MCA-EA 0429803.690   60.      17.896000                       -1.        1.
          14MCA-EB 0429803.690   60.    -102.10400                        -1.        1.
          14MCA-EC 0429803.690   60.     137.89600                        -1.        1.
          14ING-EA 0400537.460   60.     -18.018000                       -1.        1.
          14ING-EB 0400537.460   60.    -138.01800                        -1.        1.
          14ING-EC 0400537.460   60.     101.98200                        -1.        1.
          14MDN-EA 0413208.120   60.     -12.505000                       -1.        1.
          14MDN-EB 0413208.120   60.    -132.50500                        -1.        1.
          14MDN-EC 0413208.120   60.     107.49500                        -1.        1.
          14MSA-EA 0448088.150   60.     -8.8511000                       -1.        1.
          14MSA-EB 0448088.150   60.    -128.85110                        -1.        1.
          14MSA-EC 0448088.150   60.     111.14890                        -1.        1.
          14ACK-EA 0318622.130   60.     -21.693000                       -1.        1.
          14ACK-EB 0318622.130   60.    -141.69300                        -1.        1.
          14ACK-EC 0318622.130   60.      98.307000                       -1.        1.
          14NIC-EA 0450609.600   60.     -19.416000                       -1.        1.
          14NIC-EB 0450609.600   60.    -139.41600                        -1.        1.
          14NIC-EC 0450609.600   60.     100.58400                        -1.        1.
          14REV-EA 0427298.100   60.      2.7086000                       -1.        1.
          14REV-EB 0427298.100   60.    -117.29140                        -1.        1.
          14REV-EC 0427298.100   60.     122.70860                        -1.        1.
          14MON-EA 0452996.250   60.     -35.425000                       -1.        1.
          14MON-EB 0452996.250   60.    -155.42500                        -1.        1.
          14MON-EC 0452996.250   60.      84.575000                       -1.        1.

            VT1N.AVT1N.BVT1N.CVT1S.AVT1S.BVT1S.C

          *
           END OF RUN

          .........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 24 (cont'd)

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Listing of SH11002 at 10:46:01 on APR 12, 1986 for CCid=BRWG                                        Page    1

H11002: INTERNAL 5L1 A-B FAULT (KDY S, 0 OHMS)      :                     2  60.    60.
65.10417-666.66667-3 -1  0  1         00
C65.10417-666.66667-3 -1  0  1         00
C                                         :
C-----------------------------------------------------
C Compiled: 19860317                    Source: H10006 -
C                                                     -
C                         INTERNAL-FAULT              -
C                                                     -
C     Equivalent south of WSN                         -
C                                                     -
C     DL fault on KDY1SA-KDY1SB                       -
C        Fault resistance: 0.0   Ohms                 -
C        Point-on-wave:    143.13 degrees of KDY1S Vab -
C        Fault instant:    3.7806 msec                -
C                                                     -
  KDY1SAFAULT1                0.001                                         1
  KDY1SBFAULT2                0.001
C-----------------------------------------------------
C
C   19860307: GMS reactors moved from bus to 5L1 and 5L2
C
C     Peace River simulation. Full 1984 500KV B.C. Hydro network from
C Jack Sawada of B.C. Hydro, supplemented by Peace transmission
C lines extracted from a case from Brent Hughes of B.C. Hydro.
C (All data applies to 1984 system, and was obtained 13 Sept. 1985.)
C North Coast transmission is original data.
C Thevenin equivalent sources for GMS, PCN, WSN, REV, ACK, NIC, MCA,
C MSA, GLN, TKW, SKA, MDN, ING, SEL, CKY, and KLY were
C obtained from SLG fault study results from B.C. Hydro.
C
C     Study step size is 65 microseconds, giving a study bandwidth
C of about 5 KHz. Study simulation time is 67 milliseconds,
C corresponding to four power-frequency cycles. There are 256
C time points/cycle.
C
C     Transmission-line lengths for Peace River transmission have
C been adjusted to produce equal past-history interpolation
C requirements for both positive and zero sequence, so as to
C minimize errors caused by linear interpolation within program.
C
C     Peace River electrical network follows:
C
C     GMS Thevenin source:
C        (GMS-E is GMS internal voltage node)
C     GMS X/R ratio is based on B.C. Hydro standard CT specification
C        allowing for 0.1 second time constant (-> X/R=37.6999)
C        Thus ZS has 2.65% R added.
 1GMS-EAGMS..A           .5756 21.700
 2GMS-EBGMS..B                -5.227      .5756 21.700
 3GMS-ECGMS..C                -5.227           -5.227      .5756 21.700
C
C     GMS shunt reactors (2 units--one each 5L1 and 5L2)
  VT1N.A                 5.0   2040.
  VT1N.B      VT1N.A
  VT1N.C      VT1N.A

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2
```

Fig. 25. Listing of EMTP data for reduced power system model

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Listing of SH11002 at 10:46:01 on APR 12, 1986 for CCId=BRWG                                                              Page    2

  VT2N.A      VT1N.A
  VT2N.B      VT1N.A
  VT2N.C      VT1N.A
C
C     5L1 CT is from GMS to 5L1N
C     5L1 CVT is at VT1N
C
C     North end 5L1 closing resistors and switch-isolating impedances
C      Also used for current measurement
  GMS..A5L1N.A                    0.01                                              1
  GMS..B5L1N.BGMS..A5L1N.A                                                          1
  GMS..C5L1N.CGMS..A5L1N.A                                                          1
  CB1N1ACB1N2AGMS..A5L1N.A
  CB1N1BCB1N2BGMS..A5L1N.A
  CB1N1CCB1N2CGMS..A5L1N.A
  CB1N1AVT1N.A              400.
  CB1N1BVT1N.BCB1N1AVT1N.A
  CB1N1CVT1N.CCB1N1AVT1N.A
  GMS..A5L2N.AGMS..A5L1N.A
  GMS..B5L2N.BGMS..A5L1N.A
  GMS..C5L2N.CGMS..A5L1N.A
  CB2N1ACB2N2AGMS..A5L1N.A
  CB2N1BCB2N2BGMS..A5L1N.A
  CB2N1CCB2N2CGMS..A5L1N.A
  CB2N1AVT2N.ACB1N1AVT1N.A
  CB2N1BVT2N.BCB1N1AVT1N.A
  CB2N1CVT2N.CCB1N1AVT1N.A
C
C     5L1 AND 5L2 from GMS to junction with 5L3 from PCN
C        Data length-adjusted from Brent Hughes case, lengths
C        in miles. Untransposed line model.
-1VT1N.CL1-1.C              0.5877780.310988E4 26.00 1   6
-2VT1N.BL1-1.B              0.0421433.681589E4 26.00 1   6
-3VT1N.AL1-1.A              0.0403283.781798E4 26.00 1   6
-4VT2N.CL2-1.C              0.0399274.951823E4 26.00 1   6
-5VT2N.BL2-1.B              0.0399230.431848E4 26.00 1   6
-6VT2N.AL2-1.A              0.0400232.311847E4 26.00 1   6
 0.41879E 00-0.51633E 00-0.50625E 00 0.45368E 00-0.24886E 00-0.29476E 00
 0.37742E 00-0.39719E 00-0.12909E-01-0.16135E 00 0.54392E 00 0.57587E 00
 0.42676E 00-0.27482E 00 0.49348E 00-0.51708E 00-0.37640E 00-0.28544E 00
 0.42676E 00 0.27482E 00 0.49348E 00 0.51708E 00 0.37640E 00-0.28544E 00
 0.37742E 00 0.39719E 00-0.12909E-01 0.16135E 00-0.54392E 00 0.57587E 00
 0.41879E 00 0.51633E 00-0.50625E 00-0.45368E 00 0.24886E 00-0.29476E 00
C
C     PCN Thevenin source:
C        (PCN-E is PCN internal voltage node)
C     PCN X/R ratio is based on B.C. Hydro standard CT specification
C        allowing for 0.1 second time constant (-> X/R=37.6999)
C        Thus ZS has 2.65% R added.
 1PCN-EAPCN..A              2.496994.130
 2PCN-EBPCN..B                    -24.92      2.496994.130
 3PCN-ECPCN..C                    -24.92            -24.92      2.496994.130
C
C     PCN shunt reactors (1 unit):
  PCN..A                    5.    2040.
  PCN..B                    5.    2040.

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 25 (cont'd)

```
  PCN..C                          5.    2040.
C
C      5L4 from PCN to GMS
C         Data length-adjusted from solitary 5L3 data from Brent
C         Hughes case, lengths in miles. Untransposed line model.
C         Line length increase by 40% so travel time exceeds step
C         size.
C
-1PCN..CGMS..C                   0.3229627.531188E4 12.03 1   3
-2PCN..BGMS..B                   0.0489283.271806E4 12.03 1   3
-3PCN..AGMS..A                   0.0488234.601847E4 12.03 1   3
 0.59747E 00-0.70711E 00-0.41230E 00
 0.53479E 00 0.20486E-12 0.81240E 00
 0.59747E 00 0.70711E 00-0.41230E 00
C
C      5L3 from PCN to junction with 5L1 and 5L2 from GMS
C         Data length-adjusted from Brent Hughes case,
C         lengths in miles. Untransposed line model.
-1PCN..CL3-1.C                   0.3229627.531188E4 26.00 1   3
-2PCN..BL3-1.B                   0.0489283.271806E4 26.00 1   3
-3PCN..AL3-1.A                   0.0488234.601847E4 26.00 1   3
 0.59747E 00-0.70711E 00-0.41230E 00
 0.53479E 00 0.20486E-12 0.81240E 00
 0.59747E 00 0.70711E 00-0.41230E 00
C
C      5L1, 5L2, and 5L3 from junction to first transposition point:
C         Data length-adjusted from Brent Hughes case, lengths in
C         miles. Untransposed line model.
C      Transposition occurs at sending end of this line section
C         for 5L3
-1L3-1.AL3-2.A                   0.8582895.000891E4 33.24 1   9
-2L3-1.CL3-2.C                   0.0511497.861460E4 33.24 1   9
-3L3-1.BL3-2.B                   0.0435409.941654E4 33.24 1   9
-4L1-1.CL1-2.C                   0.0372253.001799E4 33.24 1   9
-5L1-1.BL1-2.B                   0.0326205.261816E4 33.24 1   9
-6L1-1.AL1-2.A                   0.0331215.861828E4 33.24 1   9
-7L2-1.CL2-2.C                   0.0484232.461848E4 33.24 1   9
-8L2-1.BL2-2.B                   0.0398229.131848E4 33.24 1   9
-9L2-1.AL2-2.A                   0.0398231.091847E4 33.24 1   9
 0.32842E 00-0.44279E 00-0.38542E 00-0.31701E 00-0.48216E 00 0.23342E 00
-0.38674E 00-0.34537E-01-0.28830E-01
 0.29533E 00-0.37922E 00-0.25754E 00-0.41833E-01 0.70848E-01-0.11350E 00
 0.79290E 00 0.26841E-01 0.21073E-01
 0.33557E 00-0.36222E 00-0.10221E 00 0.27311E 00 0.54407E 00-0.29908E 00
-0.46379E 00 0.46756E-01 0.44760E-01
 0.35685E 00-0.13903E 00 0.42073E 00 0.44855E 00 0.47026E-02 0.53196E 00
 0.56800E-01-0.35236E 00-0.27719E 00
 0.32061E 00-0.15227E-01 0.45688E 00 0.29694E-01-0.19301E 00 0.13271E-01
 0.55685E-02 0.64282E 00 0.43423E 00
 0.35848E 00 0.10766E 00 0.43398E 00-0.41918E 00-0.10699E 00-0.53441E 00
-0.11166E-01-0.40051E 00-0.17183E 00
 0.34970E 00 0.37001E 00-0.82757E-01-0.43325E 00 0.39258E 00 0.29025E 00
-0.21875E-02 0.30158E 00-0.36355E 00
 0.30747E 00 0.39077E 00-0.24091E 00 0.13323E-01 0.84531E-01 0.13409E 00
 0.17366E-02-0.41258E 00 0.67345E 00
 0.34145E 00 0.45603E 00-0.36662E 00 0.44814E 00-0.34472E 00-0.26097E 00

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 25 (cont'd)

```
 0.20493E-02 0.18335E 00-0.33728E 00
C
C     5L1 and 5L2 from first transposition point to KDY series
C        capacitor bank. Data length-adjusted from Brent Hughes
C        case, lengths in miles.
C     Transposition occurs at sending end for all three lines.
-1L1-2.BKDY1NB             0.5961780.300988E4 26.00 1   6
-2L1-2.AKDY1NA             0.0505433.631589E4 26.00 1   6
-3L1-2.CKDY1NC             0.0486283.781798E4 26.00 1   6
-4L2-2.BKDY2NB             0.0482274.771823E4 26.00 1   6
-5L2-2.AKDY2NA             0.0482230.261848E4 26.00 1   6
-6L2-2.CKDY2NC             0.0484232.311847E4 26.00 1   6
 0.41882E 00-0.51607E 00-0.50617E 00 0.45229E 00-0.25116E 00-0.29485E 00
 0.37737E 00-0.39742E 00-0.13064E-01-0.15798E 00 0.54457E 00 0.57589E 00
 0.42678E 00-0.27486E 00 0.49356E 00-0.51914E 00-0.37373E 00-0.28531E 00
 0.42678E 00 0.27486E 00 0.49356E 00 0.51914E 00 0.37373E 00-0.28531E 00
 0.37737E 00 0.39742E 00-0.13064E-01 0.15798E 00-0.54457E 00 0.57589E 00
 0.41882E 00 0.51607E 00-0.50617E 00-0.45229E 00 0.25116E 00-0.29485E 00
C
C     5L3 from first transposition point to KDY series
C        capacitor bank. Data length-adjusted from Brent Hughes
C        case, lengths in miles.
-1L3-2.BKDY3NB             0.3229627.531188E4 26.00 1   3
-2L3-2.AKDY3NA             0.0489283.271806E4 26.00 1   3
-3L3-2.CKDY3NC             0.0488234.601847E4 26.00 1   3
 0.59747E 00-0.70711E 00-0.41230E 00
 0.53479E 00 0.20486E-12 0.81240E 00
 0.59747E 00 0.70711E 00-0.41230E 00
C
C     KDY series capacitor bank:
C     Detailed series capacitor model with protective gap
C        modified from data from Brent Hughes
C        5L1 Phase A:
  KDY1NAKD1NOA                     1.89-3
  KD1NOAKD1N2A             0.0020.18850
  KD1N2AKD1N1A             3.20001.89-3
  KD1N3AKD1M.AKDY1NAKD1NOA
  KD1NOAKD1M.A             0.01007.54-343960.
  KD1M.A                               2.4504
  KD1M.AKDY1SAKD1NOAKD1M.A
  KD1S3AKD1M.AKDY1NAKD1NOA
  KD1S2AKD1S1AKD1N2AKD1N1A
  KD1S2AKDY1SAKD1NOAKD1N2A
C        5L1 Phase B:
  KDY1NBKD1NOBKDY1NAKD1NOA
  KD1NOBKD1N2BKD1NOAKD1N2A
  KD1N2BKD1N1BKD1N2AKD1N1A
  KD1N3BKD1M.BKDY1NAKD1NOA
  KD1NOBKD1M.BKD1NOAKD1M.A
  KD1M.B      KD1M.A
  KD1M.BKDY1SBKD1NOAKD1M.A
  KD1S3BKD1M.BKDY1NAKD1NOA
  KD1S2BKD1S1BKD1N2AKD1N1A
  KD1S2BKDY1SBKD1NOAKD1N2A
C        5L1 Phase C:
  KDY1NCKD1NOCKDY1NAKD1NOA

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 25 (cont'd)

```
      KD1NOCKD1N2CKD1NOAKD1N2A
      KD1N2CKD1N1CKD1N2AKD1N1A
      KD1N3CKD1M.CKDY1NAKD1NOA
      KD1NOCKD1M.CKD1NOAKD1M.A
      KD1M.C      KD1M.A
      KD1M.CKDY1SCKD1NOAKD1M.A
      KD1S3CKD1M.CKDY1NAKD1NOA
      KD1S2CKD1S1CKD1N2AKD1N1A
      KD1S2CKDY1SCKD1NOAKD1N2A
C
C          5L2 Phase A:
      KDY2NAKD2NOAKDY1NAKD1NOA
      KD2NOAKD2N2AKD1NOAKD1N2A
      KD2N2AKD2N1AKD1N2AKD1N1A
      KD2N3AKD2M.AKDY1NAKD1NOA
      KD2NOAKD2M.AKD1NOAKD1M.A
      KD2M.A      KD1M.A
      KD2M.AKDY2SAKD1NOAKD1M.A
      KD2S3AKD2M.AKDY1NAKD1NOA
      KD2S2AKD2S1AKD1N2AKD1N1A
      KD2S2AKDY2SAKD1NOAKD1N2A
C          5L2 Phase B:
      KDY2NBKD2NOBKDY1NAKD1NOA
      KD2NOBKD2N2BKD1NOAKD1N2A
      KD2N2BKD2N1BKD1N2AKD1N1A
      KD2N3BKD2M.BKDY1NAKD1NOA
      KD2NOBKD2M.BKD1NOAKD1M.A
      KD2M.B      KD1M.A
      KD2M.BKDY2SBKD1NOAKD1M.A
      KD2S3BKD2M.BKDY1NAKD1NOA
      KD2S2BKD2S1BKD1N2AKD1N1A
      KD2S2BKDY2SBKD1NOAKD1N2A
C          5L2 Phase C:
      KDY2NCKD2NOCKDY1NAKD1NOA
      KD2NOCKD2N2CKD1NOAKD1N2A
      KD2N2CKD2N1CKD1N2AKD1N1A
      KD2N3CKD2M.CKDY1NAKD1NOA
      KD2NOCKD2M.CKD1NOAKD1M.A
      KD2M.C      KD1M.A
      KD2M.CKDY2SCKD1NOAKD1M.A
      KD2S3CKD2M.CKDY1NAKD1NOA
      KD2S2CKD2S1CKD1N2AKD1N1A
      KD2S2CKDY2SCKD1NOAKD1N2A
C
C          5L3 Phase A:
      KDY3NAKD3NOAKDY1NAKD1NOA
      KD3NOAKD3N2AKD1NOAKD1N2A
      KD3N2AKD3N1AKD1N2AKD1N1A
      KD3N3AKD3M.AKDY1NAKD1NOA
      KD3NOAKD3M.A                0.01007.54-343480.
      KD3M.A      KD1M.A
      KD3M.AKDY3SAKD3NOAKD3M.A
      KD3S3AKD3M.AKDY1NAKD1NOA
      KD3S2AKD3S1AKD1N2AKD1N1A
      KD3S2AKDY3SAKD1NOAKD1N2A
C          5L3 Phase B:

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 25 (cont'd)

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Listing of SH11002 at 10:46:01 on APR 12, 1986 for CCid=BRWG                                    Page    6

          KDY3NBKD3NOBKDY1NAKD1NOA
          KD3NOBKD3N2BKD1NOAKD1N2A
          KD3N2BKD3N1BKD1N2AKD1N1A
          KD3N3BKD3M.BKDY1NAKD1NOA
          KD3NOBKD3M.BKD3NOAKD3M.A
          KD3M.B      KD1M.A
          KD3M.BKDY3SBKD3NOAKD3M.A
          KD3S3BKD3M.BKDY1NAKD1NOA
          KD3S2BKD3S1BKD1N2AKD1N1A
          KD3S2BKDY3SBKD1NOAKD1N2A
C             5L3 Phase C:
          KDY3NCKD3NOCKDY1NAKD1NOA
          KD3NOCKD3N2CKD1NOAKD1N2A
          KD3N2CKD3N1CKD1N2AKD1N1A
          KD3N3CKD3M.CKDY1NAKD1NOA
          KD3NOCKD3M.CKD3NOAKD3M.A
          KD3M.C      KD1M.A
          KD3M.CKDY3SCKD3NOAKD3M.A
          KD3S3CKD3M.CKDY1NAKD1NOA
          KD3S2CKD3S1CKD1N2AKD1N1A
          KD3S2CKDY3SCKD1NOAKD1N2A
C
C        5L1, 5L2, and 5L3 from KDY series capacitor bank to second
C            transposition point. Data length adjusted from Brent Hughes
C            case. Untransposed line model.
-1KDY1SBL1-5.B            0.8623947.820893E4 26.00 1    9
-2KDY1SAL1-5.A            0.0484478.891513E4 26.00 1    9
-3KDY1SCL1-5.C            0.0433376.011705E4 26.00 1    9
-4KDY2SBL2-5.B            0.0395271.181803E4 26.00 1    9
-5KDY2SAL2-5.A            0.0331209.701827E4 26.00 1    9
-6KDY2SCL2-5.C            0.0324202.761838E4 26.00 1    9
-7KDY3SBL3-5.B            0.0477228.751848E4 26.00 1    9
-8KDY3SAL3-5.A            0.0390226.081847E4 26.00 1    9
-9KDY3SCL3-5.C            0.0385219.921849E4 26.00 1    9
 0.35665E 00-0.47171E 00-0.42982E 00-0.44717E 00-0.35065E 00 0.23963E 00
-0.37070E-02 0.31196E 00-0.13818E 00
 0.31678E 00-0.39122E 00-0.23234E 00 0.42209E-02 0.17235E 00-0.22650E 00
-0.41552E-03-0.66235E 00 0.34511E 00
 0.34197E 00-0.33515E 00 0.13433E-01 0.42322E 00 0.40861E 00-0.22179E 00
 0.59792E-02 0.41813E 00-0.33657E 00
 0.34512E 00-0.13700E 00 0.39685E 00 0.39533E 00-0.14213E 00 0.52102E 00
 0.37371E-02 0.85572E-01 0.44310E 00
 0.32004E 00 0.14023E-01 0.45150E 00-0.33083E-01-0.32729E 00-0.58562E-01
-0.67096E-02-0.38795E 00-0.61489E 00
 0.34294E 00 0.16435E 00 0.38142E 00-0.43586E 00 0.32676E-02-0.51105E 00
-0.96139E-01 0.32200E 00 0.37778E 00
 0.32544E 00 0.32838E 00-0.11377E-01-0.31404E 00 0.49650E 00 0.32316E 00
 0.51130E 00-0.87018E-01-0.67666E-01
 0.30399E 00 0.38167E 00-0.24521E 00 0.34340E-01 0.12210E 00 0.17703E 00
-0.76882E 00-0.55044E-01-0.66979E-01
 0.34319E 00 0.46080E 00-0.43738E 00 0.37312E 00-0.40668E 00-0.23920E 00
 0.35910E 00 0.58969E-01 0.57106E-01
C
C        5L1, 5L2, and 5L3 from second transposition point to last 5L3
C            transposition point.
C            Data length-adjusted from Brent Hughes case. Untransposed

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 25 (cont'd)

```
C          line model.
C      Transposition effected at sending end of section for all three
C          lines.
-1L1-5.AL1-6.A            0.8623947.820893E4 33.24 1   9
-2L1-5.CL1-6.C            0.0484478.891513E4 33.24 1   9
-3L1-5.BL1-6.B            0.0433376.011705E4 33.24 1   9
-4L2-5.AL2-6.A            0.0395271.181803E4 33.24 1   9
-5L2-5.CL2-6.C            0.0331209.701827E4 33.24 1   9
-6L2-5.BL2-6.B            0.0324202.761838E4 33.24 1   9
-7L3-5.CL3-6.C            0.0477228.751848E4 33.24 1   9
-8L3-5.BL3-6.B            0.0390226.081847E4 33.24 1   9
-9L3-5.AL3-6.A            0.0385219.921849E4 33.24 1   9
 0.35665E 00-0.47171E 00-0.42982E 00-0.44717E 00-0.35065E 00 0.23963E 00
-0.37070E-02 0.31196E 00-0.13818E 00
 0.31678E 00-0.39122E 00-0.23234E 00 0.42209E-02 0.17235E 00-0.22650E 00
-0.41552E-03-0.66235E 00 0.34511E 00
 0.34197E 00-0.33515E 00 0.13433E-01 0.42322E 00 0.40861E 00-0.22179E 00
 0.59792E-02 0.41813E 00-0.33657E 00
 0.34512E 00-0.13700E 00 0.39685E 00 0.39533E 00-0.14213E 00 0.52102E 00
 0.37371E-02 0.85572E-01 0.44310E 00
 0.32004E 00 0.14023E-01 0.45150E 00-0.33083E-01-0.32729E 00-0.58562E-01
-0.67096E-02-0.38795E 00-0.61489E 00
 0.34294E 00 0.16435E 00 0.38142E 00-0.43586E 00 0.32675E-02-0.51105E 00
-0.96139E-01 0.32200E 00 0.37778E 00
 0.32544E 00 0.32838E 00-0.11377E-01-0.31404E 00 0.49650E 00 0.32316E 00
 0.51130E 00-0.87018E-01-0.67666E-01
 0.30399E 00 0.38167E 00-0.24521E 00 0.34340E-01 0.12210E 00 0.17703E 00
-0.76882E 00-0.55044E-01-0.66979E-01
 0.34319E 00 0.46080E 00-0.43738E 00 0.37312E 00-0.40668E 00-0.23920E 00
 0.35910E 00 0.58969E-01 0.57106E-01
C
C      5L1, 5L2, and 5L3 from last 5L3 transposition point to WSN.
C          Data length adjusted from Brent Hughes case. Untransposed
C          line model. Lengths in miles.
C      Transposition of 5L3 effected at sending end of this section.
-1L1-6.AVT1S.A            0.8623947.820893E4 26.00 1   9
-2L1-6.CVT1S.C            0.0484478.891513E4 26.00 1   9
-3L1-6.BVT1S.B            0.0433376.011705E4 26.00 1   9
-4L2-6.AVT2S.A            0.0395271.181803E4 26.00 1   9
-5L2-6.CVT2S.C            0.0331209.701827E4 26.00 1   9
-6L2-6.BVT2S.B            0.0324202.761838E4 26.00 1   9
-7L3-6.AWSN..A            0.0477228.751848E4 26.00 1   9
-8L3-6.CWSN..C            0.0390226.081847E4 26.00 1   9
-9L3-6.BWSN..B            0.0385219.921849E4 26.00 1   9
 0.35665E 00-0.47171E 00-0.42982E 00-0.44717E 00-0.35065E 00 0.23963E 00
-0.37070E-02 0.31196E 00-0.13818E 00
 0.31678E 00-0.39122E 00-0.23234E 00 0.42209E-02 0.17235E 00-0.22650E 00
-0.41552E-03-0.66235E 00 0.34511E 00
 0.34197E 00-0.33515E 00 0.13433E-01 0.42322E 00 0.40861E 00-0.22179E 00
 0.59792E-02 0.41813E 00-0.33657E 00
 0.34512E 00-0.13700E 00 0.39685E 00 0.39533E 00-0.14213E 00 0.52102E 00
 0.37371E-02 0.85572E-01 0.44310E 00
 0.32004E 00 0.14023E-01 0.45150E 00-0.33083E-01-0.32729E 00-0.58562E-01
-0.67096E-02-0.38795E 00-0.61489E 00
 0.34294E 00 0.16435E 00 0.38142E 00-0.43586E 00 0.32675E-02-0.51105E 00
-0.96139E-01 0.32200E 00 0.37778E 00

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 25 (cont'd)

```
 0.32544E 00 0.32838E 00-0.11377E-01-0.31404E 00 0.49650E 00 0.32316E 00
 0.51130E 00-0.87018E-01-0.67666E-01
 0.30399E 00 0.38167E 00-0.24521E 00 0.34340E-01 0.12210E 00 0.17703E 00
-0.76882E 00-0.55044E-01-0.66979E-01
 0.34319E 00 0.46080E 00-0.43738E 00 0.37312E 00-0.40668E 00-0.23920E 00
 0.35910E 00 0.58969E-01 0.57106E-01
C
C     South end 5L1 closing resistors and switch-isolating impedances
C      Also used for current measurement
  VT1S.ACB1S1ACB1N1AVT1N.A
  VT1S.BCB1S1BCB1N1AVT1N.A
  VT1S.CCB1S1CCB1N1AVT1N.A
  CB1S2ACB1S1AGMS..A5L1N.A
  CB1S2BCB1S1BGMS..A5L1N.A
  CB1S2CCB1S1CGMS..A5L1N.A
  WSN..A5L1S.AGMS..A5L1N.A                                                     1
  WSN..B5L1S.BGMS..A5L1N.A                                                     1
  WSN..C5L1S.CGMS..A5L1N.A                                                     1
  VT2S.ACB2S1ACB1N1AVT1N.A
  VT2S.BCB2S1BCB1N1AVT1N.A
  VT2S.CCB2S1CCB1N1AVT1N.A
  CB2S2ACB2S1AGMS..A5L1N.A
  CB2S2BCB2S1BGMS..A5L1N.A
  CB2S2CCB2S1CGMS..A5L1N.A
  WSN..A5L2S.AGMS..A5L1N.A
  WSN..B5L2S.BGMS..A5L1N.A
  WSN..C5L2S.CGMS..A5L1N.A
C
C     5L1 CT is from WSN to 5L1S
C     5L1 CVT is at VT1S
C
C     WSN Thevenin source:
C        (WSN-E is WSN internal voltage node)
 1WSN-EAWSN..A            3.724443.127
 2WSN-EBWSN..B            -.19332.3852      3.724443.127
 3WSN-ECWSN..C            -.19332.3852      -.19332.3852      3.724443.127
C
C     WSN shunt reactors (2 units):
  WSN..A                  2.5   1020.
  WSN..B                  2.5   1020.
  WSN..C                  2.5   1020.
C
C     end of network

  FAULT1FAULT23.780583-31.00000000
  5L1N.ACB1N1A-1.       1.0          30.0
  5L1N.BCB1N1B-1.       1.0          30.0
  5L1N.CCB1N1C-1.       1.0          30.0
  CB1N2AVT1N.A-1.       1.0          30.0
  CB1N2BVT1N.B-1.       1.0          30.0
  CB1N2CVT1N.C-1.       1.0          30.0
  5L1S.ACB1S1A-1.       1.0          30.0
  5L1S.BCB1S1B-1.       1.0          30.0
  5L1S.CCB1S1C-1.       1.0          30.0
  CB1S2AVT1S.A-1.       1.0          30.0
  CB1S2BVT1S.B-1.       1.0          30.0

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 25 (cont'd)

```
Listing of SH11002 at 10:46:01 on APR 12, 1986 for CCid=BRWG                                      Page    9

   449       CB1S2CVT1S.C-1.      1.0          30.0
   450       5L2N.ACB2N1A-1.      1.0          30.0
   451       5L2N.BCB2N1B-1.      1.0          30.0
   452       5L2N.CCB2N1C-1.      1.0          30.0
   453       CB2N2AVT2N.A-1.      1.0          30.0
   454       CB2N2BVT2N.B-1.      1.0          30.0
   455       CB2N2CVT2N.C-1.      1.0          30.0
   456       CB2S1A5L2S.A-1.      1.0          30.0
   457       CB2S1B5L2S.B-1.      1.0          30.0
   458       CB2S1C5L2S.C-1.      1.0          30.0
   459       CB2S2AVT2S.A-1.      1.0          30.0
   460       CB2S2BVT2S.B-1.      1.0          30.0
   461       CB2S2CVT2S.C-1.      1.0          30.0
   462       KD1NOAKD1N1AO.       .083      30.0      10000.
   463       KD1N2AKD1N3AO.       .083      30.0      190890.
   464       KDY1SAKD1S1AO.       .083      30.0      10000.
   465       KD1S2AKD1S3AO.       .083      30.0      190890.
   466       KD1NOBKD1N1BO.       .083      30.0      10000.
   467       KD1N2BKD1N3BO.       .083      30.0      190890.
   468       KDY1SBKD1S1BO.       .083      30.0      10000.
   469       KD1S2BKD1S3BO.       .083      30.0      190890.
   470       KD1NOCKD1N1CO.       .083      30.0      10000.
   471       KD1N2CKD1N3CO.       .083      30.0      190890.
   472       KDY1SCKD1S1CO.       .083      30.0      10000.
   473       KD1S2CKD1S3CO.       .083      30.0      190890.
   474       KD2NOAKD2N1AO.       .083      30.0      10000.
   475       KD2N2AKD2N3AO.       .083      30.0      190890.
   476       KDY2SAKD2S1AO.       .083      30.0      10000.
   477       KD2S2AKD2S3AO.       .083      30.0      190890.
   478       KD2NOBKD2N1BO.       .083      30.0      10000.
   479       KD2N2BKD2N3BO.       .083      30.0      190890.
   480       KDY2SBKD2S1BO.       .083      30.0      10000.
   481       KD2S2BKD2S3BO.       .083      30.0      190890.
   482       KD2NOCKD2N1CO.       .083      30.0      10000.
   483       KD2N2CKD2N3CO.       .083      30.0      190890.
   484       KDY2SCKD2S1CO.       .083      30.0      10000.
   485       KD2S2CKD2S3CO.       .083      30.0      190890.
   486       KD3NOAKD3N1AO.       .083      30.0      10000.
   487       KD3N2AKD3N3AO.       .083      30.0      192420.
   488       KDY3SAKD3S1AO.       .083      30.0      10000.
   489       KD3S2AKD3S3AO.       .083      30.0      192420.
   490       KD3NOBKD3N1BO.       .083      30.0      10000.
   491       KD3N2BKD3N3BO.       .083      30.0      192420.
   492       KDY3SBKD3S1BO.       .083      30.0      10000.
   493       KD3S2BKD3S3BO.       .083      30.0      192420.
   494       KD3NOCKD3N1CO.       .083      30.0      10000.
   495       KD3N2CKD3N3CO.       .083      30.0      192420.
   496       KDY3SCKD3S1CO.       .083      30.0      10000.
   497       KD3S2CKD3S3CO.       .083      30.0      192420.
   498
   499     14GMS-EA 0425767.790   60.     46.201000                      -1.        1.
   500     14GMS-EB 0425767.790   60.    -73.799000                      -1.        1.
   501     14GMS-EC 0425767.790   60.     166.20100                      -1.        1.
   502     14PCN-EA 0425815.370   60.     49.345000                      -1.        1.
   503     14PCN-EB 0425815.370   60.    -70.655000                      -1.        1.
   504     14PCN-EC 0425815.370   60.     169.34500                      -1.        1.

         .........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 25 (cont'd)

```
Listing of SH11002 at 10:46:01 on APR 12, 1986 for CCid=BRWG                                                Page   10

     14WSN-EA 0470553.000   60.    - 4.730900                       -1.       1.
     14WSN-EB 0470553.000   60.    -124.73090                       -1.       1.
     14WSN-EC 0470553.000   60.     115.26910                       -1.       1.

       VT1N.AVT1N.BVT1N.CVT1S.AVT1S.BVT1S.C


      END OF RUN

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 25 (cont'd)

APPENDIX B

PROTECTION MODEL

A. *TRP PROTECTION SIMULATION*

The operation of the protection for the B.C. Hydro Peace River transmission line 5L1 has been described in chapter V. Figure 26 shows a listing of the TRP commands which simulate this protection.

The Williston phase-fault protection is simulated first (lines 5-112) followed by the Williston ground-fault protection (lines 113-210). The G.M. Shrum relays are simulated next: the phase-fault protection first (lines 214-332), followed by the ground-fault protection (lines 333-430). Finally the Williston and G.M. Shrum signals are combined in the permissive trip block according to the permissive- and transfer-trip logic (lines 431-447).

B. *USER FUNCTION DESCRIPTIONS*

This section describes the special TRP user functions which were written to allow modelling of the 5L1 protection.

1. AND

The AND function is performed as an NLR operation (see chapter III). The output is thus the algebraic minimum of the inputs. Only two inputs are available for this implementation, although more could have been provided.† The AND function is implemented as an alias of the TRP internal function MINIMUM.

†This presents only a minor annoyance in practice, since multiple two-input AND functions can easily be cascaded to get a multiple-input AND function.

```
COMM          SIMULATION FOR 5L1 PROTECTION (19860927)
COMM          NEW PERMISSIVE TRIP BLOCK
COMM
COMM       WSN-END PROTECTION
COMM
COMM       COMPUTE DELTA VOLTAGES
COMPUTE CV:WVAB=SUBTRACT(NV:VT1S.A,NV:VT1S.B)
COMPUTE CV:WVBC=SUBTRACT(NV:VT1S.B,NV:VT1S.C)
COMPUTE CV:WVCA=SUBTRACT(NV:VT1S.C,NV:VT1S.A)
COMM       COMPUTE DELTA CURRENTS
COMPUTE CV:WIAB=SUBTRACT(BC:WSN..A:5L1S.A,BC:WSN..B:5L1S.B)
COMPUTE CV:WIBC=SUBTRACT(BC:WSN..B:5L1S.B,BC:WSN..C:5L1S.C)
COMPUTE CV:WICA=SUBTRACT(BC:WSN..C:5L1S.C,BC:WSN..A:5L1S.A)
COMM
COMM       PHASE-FAULT RELAYS
COMM        21LX FILTER-SWITCHING RELAY
COMPUTE CV:21LX=SDX1H(CV:WVAB,CV:WVBC,CV:WVCA,360E3,22.5E3,.33,.33)
PLOT HOLD Y-RANGE=(19.9,-19.9) Y-UNITS= -
PLOT Y-LABEL="WSN 21LX Q-SWITCHING OUTPUT" TRACE(2)=CV:21LX(0) -
PLOT Y-LABEL="WSN 21LX INSERT DELAY OUTPUT" TRACE(1)=CV:21LX(1) -
DISPLAY RANGE=CV:21LX(0);CV:21LX(1)
COMM      21L1 ZONE 1 (UNDERREACHING) DISTANCE RELAY
COMPUTE CV:21L1AB=SD2H(CV:WVAB,CV:WIAB,CV:21LX(0),CV:21LX(1),35.4,85,10,1,5,40E-3,82.5,.33)
DISPLAY RANGE=CV:21L1AB
COMPUTE CV:21L1BC=SD2H(CV:WVBC,CV:WIBC,CV:21LX(0),CV:21LX(1),35.4,85,10,1,5,40E-3,82.5,.33)
DISPLAY RANGE=CV:21L1BC
COMPUTE CV:TMPO=OR(CV:21L1AB,CV:21L1BC)
DELETE ENTRY=CV:21L1AB;CV:21L1BC
COMPUTE CV:21L1CA=SD2H(CV:WVCA,CV:WICA,CV:21LX(0),CV:21LX(1),35.4,85,10,1,5,40E-3,82.5,.33)
DISPLAY RANGE=CV:21L1CA
COMPUTE CV:21L1=OR(CV:21L1CA,CV:TMPO)
DELETE ENTRY=CV:21L1CA;CV:TMPO
DISPLAY RANGE=CV:21L1
PLOT Y-LABEL="WSN 21L1" TRACE(5)=CV:21L1 -
COMM      21L2 ZONE 2 (OVERREACHING) DISTANCE RELAY
COMPUTE CV:21L2AB=SD2H(CV:WVAB,CV:WIAB,CV:21LX(0),CV:21LX(1),123,85,10,1,5,40E-3,82.5,.33)
DELETE ENTRY=CV:WVAB
DISPLAY RANGE=CV:21L2AB
COMPUTE CV:21L2BC=SD2H(CV:WVBC,CV:WIBC,CV:21LX(0),CV:21LX(1),123,85,10,1,5,40E-3,82.5,.33)
DELETE ENTRY=CV:WVBC
DISPLAY RANGE=CV:21L2BC
COMPUTE CV:TMPO=OR(CV:21L2AB,CV:21L2BC)
DELETE ENTRY=CV:21L2AB;CV:21L2BC
COMPUTE CV:21L2CA=SD2H(CV:WVCA,CV:WICA,CV:21LX(0),CV:21LX(1),123,85,10,1,5,40E-3,82.5,.33)
DISPLAY RANGE=CV:21L2CA
COMPUTE CV:21L2=OR(CV:21L2CA,CV:TMPO)
DELETE ENTRY=CV:21L2CA;CV:TMPO;CV:WVCA;CV:WICA;CV:WIBC;CV:WIAB
DISPLAY RANGE=CV:21L2
PLOT Y-LABEL="WSN 21L2" TRACE(4)=CV:21L2 -
COMM      21L3 ZONE 3 (REVERSE BLOCKING) DISTANCE RELAY
COMM      NEGATE CURRENTS--21L3 CT IS REVERSE LOOKING
COMPUTE CV:IA=NEGATE(BC:WSN..A:5L1S.A)
COMPUTE CV:IB=NEGATE(BC:WSN..B:5L1S.B)
COMPUTE CV:IC=NEGATE(BC:WSN..C:5L1S.C)
COMM      LOAD ANGLE COMPENSATOR
COMPUTE CV:LACA=LAC(CV:IA,33.77)

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 26. Listing of TRP data for 5L1 protection simulations

```
COMPUTE CV:LACB=LAC(CV:IB,33,77)
COMPUTE CV:LACC=LAC(CV:IC,33,77)
COMPUTE CV:VA=ADD(NV:VT1S.A,CV:LACA)
COMPUTE CV:VB=ADD(NV:VT1S.B,CV:LACB)
COMPUTE CV:VC=ADD(NV:VT1S.C,CV:LACC)
DELETE ENTRY=CV:LACA;CV:LACB;CV:LACC
COMPUTE CV:VAB=SUBTRACT(CV:VA,CV:VB)
COMPUTE CV:VBC=SUBTRACT(CV:VB,CV:VC)
COMPUTE CV:VCA=SUBTRACT(CV:VC,CV:VA)
DELETE ENTRY=CV:VA;CV:VB;CV:VC
COMPUTE CV:IAB=SUBTRACT(CV:IA,CV:IB)
COMPUTE CV:IBC=SUBTRACT(CV:IB,CV:IC)
COMPUTE CV:ICA=SUBTRACT(CV:IC,CV:IA)
DELETE ENTRY=CV:IA;CV:IB;CV:IC
COMM     FILTER DROPOUT DELAY
COMPUTE CV:FILTERX=TIMER(CV:21LX(0),0,60E-3)
DISPLAY RANGE=CV:FILTERX
COMPUTE CV:21L3AB=SD2H(CV:VAB,CV:IAB,CV:FILTERX,CV:21LX(1),160.7,87.1,10,1,5,0,82.5,.33)
DELETE ENTRY=CV:VAB;CV:IAB
DISPLAY RANGE=CV:21L3AB
COMPUTE CV:21L3BC=SD2H(CV:VBC,CV:IBC,CV:FILTERX,CV:21LX(1),160.7,87.1,10,1,5,0,82.5,.33)
DELETE ENTRY=CV:VBC;CV:IBC
DISPLAY RANGE=CV:21L3BC
COMPUTE CV:TMPO=OR(CV:21L3AB,CV:21L3BC)
DELETE ENTRY=CV:21L3AB;CV:21L3BC
COMPUTE CV:21L3CA=SD2H(CV:VCA,CV:ICA,CV:FILTERX,CV:21LX(1),160.7,87.1,10,1,5,0,82.5,.33)
DELETE ENTRY=CV:VCA;CV:ICA;CV:FILTERX;CV:21LX
DISPLAY RANGE=CV:21L3CA
COMPUTE CV:21L3=OR(CV:21L3CA,CV:TMPO)
DELETE ENTRY=CV:21L3CA;CV:TMPO
DISPLAY RANGE=CV:21L3
PLOT Y-LABEL="WSN 21L3" TRACE(3)=CV:21L3 -
COMM
COMM      DISTANCE SUPERVISION CURRENT RELAYS
COMM
COMPUTE CV:50LA=OVERCURRENT.IT(BC:WSN..A:5L1S.A,268,1,.33)
COMPUTE CV:50LB=OVERCURRENT.IT(BC:WSN..B:5L1S.B,268,1,.33)
COMPUTE CV:50LC=OVERCURRENT.IT(BC:WSN..C:5L1S.C,268,1,.33)
DISPLAY RANGE=CV:50LA;CV:50LB;CV:50LC
COMM      "OR" TO GET DISTANCE SUPERVISION OUTPUT
COMPUTE CV:TMPO=OR(CV:50LA,CV:50LB)
COMPUTE CV:50L=OR(CV:50LC,CV:TMPO)
DELETE ENTRY=CV:TMPO;CV:50LA;CV:50LB;CV:50LC
DISPLAY RANGE=CV:50L
PLOT Y-LABEL="WSN 50L" TRACE(6)=CV:50L RELEASE
COMM
COMM      "AND" TO GET PHASE-FAULT DIRECT TRIP
COMPUTE CV:PFDT=AND(CV:21L1,CV:50L)
DELETE ENTRY=CV:21L1
COMM      "AND" TO GET PHASE-FAULT PERMISSIVE TRIP
COMPUTE CV:PFPT=AND(CV:21L2,CV:50L)
DELETE ENTRY=CV:21L2
display range=cv:pfdt;CV:PFPT
COMM      "AND" TO GET PHASE REVERSE BLOCKING
COMPUTE CV:PRB=AND(CV:21L3,CV:50L)
DELETE ENTRY=CV:21L3;CV:50L

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 26 (cont'd)

```
DISPLAY RANGE=CV:PRB
COMM
COMM      GROUND-FAULT RELAYS
COMM     COMPUTE 3 * ZERO-SEQUENCE VOLTAGE
COMPUTE CV:TMPO=ADD(NV:VT1S.A,NV:VT1S.B)
COMPUTE CV:TMP1=ADD(CV:TMPO,NV:VT1S.C)
COMM     FILTER 3VO FOR INPUT TO DIRECTIONAL ELEMENTS
COMPUTE CV:3VO=FILTER(CV:TMP1,1)
DELETE ENTRY=CV:TMPO;NV:VT1S.A;NV:VT1S.B;NV:VT1S.C;CV:TMP1
COMPUTE CV:PSFILTER=PS-FILTER.A(BC:WSN..A:5L1S.A,BC:WSN..B:5L1S.B,BC:WSN..C:5L1S.C)
DELETE ENTRY=BC:WSN..A:5L1S.A;BC:WSN..B:5L1S.B;BC:WSN..C:5L1S.C
COMM     FILTER 3IO FOR INPUT TO DIRECTIONAL ELEMENTS AND 5OLN/IO...
COMPUTE CV:3IO=FILTER(CV:PSFILTER(1),1)
COMM     USE INSTANTANEOUS OVERCURRENT ELEMENT FOR FINITE SENSITIVITY
COMM               (NO HYSTERESIS WANTED HERE)
COMPUTE CV:GATE=OVERCURRENT.IT(CV:3IO,50)
COMM     GATE 3IO
COMPUTE CV:G3IO=GATE(CV:3IO,CV:GATE)
COMPUTE CV:32R=DIRECTIONAL(CV:G3IO,CV:3VO,-89.5,96,.33)
COMM     NEGATE GATED 3IO FOR FORWARD ELEMENT
COMPUTE CV:NG3IO=NEGATE(CV:G3IO)
COMPUTE CV:32F=DIRECTIONAL(CV:NG3IO,CV:3VO,-89.5,85,.33)
DELETE ENTRY=CV:NG3IO;CV:3VO;CV:G3IO;CV:GATE
PLOT HOLD Y-RANGE=(-19.9,19.9) Y-UNITS= -
PLOT Y-LABEL="WSN 32F" TRACE(2)=CV:32F -
PLOT Y-LABEL="WSN 32R" TRACE(1)=CV:32R -
DISPLAY RANGE=CV:32F;CV:32R
COMM
COMM      GROUND INVERSE-TIME OVERCURRENT ELEMENT
COMPUTE CV:5OLN1S=OVERCURRENT.IT(CV:PSFILTER(1),200,1000,.33)
PLOT Y-LABEL="WSN 5OLN1S" TRACE(3)=CV:5OLN1S -
DISPLAY RANGE=CV:5OLN1S
COMM
COMM      "AND" TO GET DIRECTIONAL GROUND OVERCURRENT OUTPUT
COMPUTE CV:DGOC=AND(CV:32F,CV:5OLN1S)
DISPLAY RANGE=CV:DGOC
DELETE ENTRY=CV:5OLN1S
COMM
COMM      INSTANTANEOUS GROUND OVER-CURRENT RELAY
COMPUTE CV:RESTRAIN=COPY(CV:PSFILTER,0.2)
COMPUTE CV:5OLNIOD=OVERCURRENT.R(CV:3IO,CV:RESTRAIN,1400,630,.33)
PLOT Y-LABEL="WSN 5OLN/IOD" TRACE(6)=CV:5OLNIOD -
COMPUTE CV:5OLNIOH=OVERCURRENT.R(CV:3IO,CV:RESTRAIN,300,630,.33)
COMPUTE CV:5OLNIOL=OVERCURRENT.R(CV:3IO,CV:RESTRAIN,100,630,.33)
PLOT Y-LABEL="WSN 5OLN/IOL" TRACE(4)=CV:5OLNIOL -
PLOT Y-LABEL="WSN 5OLN/IOH" TRACE(5)=CV:5OLNIOH RELEASE
DISPLAY RANGE=CV:5OLNIOD;CV:5OLNIOH;CV:5OLNIOL
DELETE ENTRY=CV:PSFILTER;CV:RESTRAIN;CV:3IO
COMM
COMM      "OR" TO GET COMPLETE GROUND FAULT DIRECT TRIP OUTPUT
COMPUTE CV:GFDT=OR(CV:5OLNIOD,CV:DGOC)
DISPLAY RANGE=CV:GFDT
PLOT HOLD Y-RANGE=(-19.9,19.9) Y-UNITS= -
PLOT Y-LABEL="WSN GROUND FAULT DIRECT TRIP" TRACE(5)=CV:GFDT -
PLOT Y-LABEL="WSN PHASE FAULT DIRECT TRIP" TRACE(6)=CV:PFDT -
DELETE ENTRY=CV:5OLNIOD;CV:DGOC

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 26 (cont'd)

```
COMM      "AND" TO GET GROUND FAULT PERMISSIVE TRIP
COMPUTE CV:GFPT=AND(CV:5OLNIOH,CV:32F)
PLOT Y-LABEL="WSN GROUND FAULT PERMISSIVE TRIP" TRACE(3)=CV:GFPT -
PLOT Y-LABEL="WSN PHASE FAULT PERMISSIVE TRIP" TRACE(4)=CV:PFPT -
DELETE ENTRY=CV:5OLNIOH;CV:32F
COMM      "AND" TO GET GROUND REVERSE BLOCKING
COMPUTE CV:GRB=AND(CV:5OLNIOL,CV:32R)
PLOT Y-LABEL="WSN GROUND FAULT REVERSE BLOCKING" TRACE(1)=CV:GRB -
PLOT Y-LABEL="WSN PHASE FAULT REVERSE BLOCKING" TRACE(2)=CV:PRB
PLOT RELEASE
DISPLAY RANGE=CV:GFPT;CV:GRB
DELETE ENTRY=CV:5OLNIOL;CV:32R
COMM
COMM      "OR" PHASE AND GROUND DIRECT TRIP TO GET DIRECT LOCAL TRIP
COMPUTE CV:WSNDLT=OR(CV:PFDT,CV:GFDT)
DISPLAY RANGE=CV:WSNDLT
DELETE ENTRY=CV:PFDT;CV:GFDT
COMM      "OR" PHASE AND GROUND PERMISSIVE TRIP TO GET
COMM                COMBINED PERMISSIVE TRIP
COMPUTE CV:CPT=OR(CV:PFPT,CV:GFPT)
DISPLAY RANGE=CV:CPT
DELETE ENTRY=CV:PFPT;CV:GFPT
COMM      "OR" PHASE AND GROUND REVERSE BLOCKING TO GET REVERSE
COMM               BLOCKING
COMPUTE CV:RB=OR(CV:GRB,CV:PRB)
DISPLAY RANGE=CV:RB
DELETE ENTRY=CV:GRB;CV:PRB
COMM      USE DROP-OUT DELAY AND INVERSION TO GET "NO-REVERSE-BLOCKING"
COMPUTE CV:TMP=TIMER(CV:RB,0,100E-3)
DELETE ENTRY=CV:RB
COMPUTE CV:WSNNRB=NOT(CV:TMP)
DISPLAY RANGE=CV:WSNNRB
DELETE ENTRY=CV:TMP
COMM      "AND" COMBINED PERMISSIVE TRIP AND NO-REVERSE BLOCKING TO GET
COMM               LOCAL FORWARD PERMISSIVE
COMPUTE CV:WSNLFP=AND(CV:CPT,CV:WSNNRB)
PLOT TRACES/PAGE=4 HOLD Y-RANGE=(-19.9,19.9) Y-UNITS= -
PLOT Y-LABEL="WSN COMBINED PERMISSIVE TRIP" TRACE(1)=CV:CPT -
PLOT Y-LABEL="WSN NO REVERSE BLOCKING" TRACE(2)=CV:WSNNRB -
PLOT Y-LABEL="WSN LOCAL FORWARD PERMISSIVE" TRACE(3)=CV:WSNLFP -
PLOT Y-LABEL="WSN DIRECT LOCAL TRIP" TRACE(4)=CV:WSNDLT RELEASE
DELETE ENTRY=CV:CPT
DISPLAY RANGE=CV:WSNLFP
COMM
COMM            GMS-END PROTECTION
COMM
COMM           COMPUTE DELTA VOLTAGES
COMPUTE CV:GVAB=SUBTRACT(NV:VT1N.A,NV:VT1N.B)
COMPUTE CV:GVBC=SUBTRACT(NV:VT1N.B,NV:VT1N.C)
COMPUTE CV:GVCA=SUBTRACT(NV:VT1N.C,NV:VT1N.A)
COMM           COMPUTE DELTA CURRENTS
COMPUTE CV:GIAB=SUBTRACT(BC:GMS..A:5L1N.A,BC:GMS..B:5L1N.B)
COMPUTE CV:GIBC=SUBTRACT(BC:GMS..B:5L1N.B,BC:GMS..C:5L1N.C)
COMPUTE CV:GICA=SUBTRACT(BC:GMS..C:5L1N.C,BC:GMS..A:5L1N.A)
COMM
COMM      PHASE-FAULT RELAYS

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 26 (cont'd)

```
Listing of IWSNCBP at 12:41:07 on OCT  4, 1986 for CCid=BRWG                                                    Page    5

COMM       21LX FILTER-SWITCHING RELAY
COMPUTE CV:21LX=SDX1H(CV:GVAB,CV:GVBC,CV:GVCA,360E3,22.5E3,.33,.33)
PLOT HOLD Y-RANGE=(19.9,-19.9) Y-UNITS= -
PLOT Y-LABEL="GMS 21LX Q-SWITCHING OUTPUT" TRACE(2)=CV:21LX(0) -
PLOT Y-LABEL="GMS 21LX INSERT DELAY OUTPUT" TRACE(1)=CV:21LX(1) -
DISPLAY RANGE=CV:21LX(0);CV:21LX(1)
COMM      21L1 ZONE 1 (UNDERREACHING) DISTANCE RELAY
COMPUTE CV:21L1AB=SD2H(CV:GVAB,CV:GIAB,CV:21LX(0),CV:21LX(1),35.4,85,10,1,5,40E-3,82.5,.33)
DISPLAY RANGE=CV:21L1AB
COMPUTE CV:21L1BC=SD2H(CV:GVBC,CV:GIBC,CV:21LX(0),CV:21LX(1),35.4,85,10,1,5,40E-3,82.5,.33)
DISPLAY RANGE=CV:21L1BC
COMPUTE CV:TMPO=OR(CV:21L1AB,CV:21L1BC)
DELETE ENTRY=CV:21L1AB;CV:21L1BC
COMPUTE CV:21L1CA=SD2H(CV:GVCA,CV:GICA,CV:21LX(0),CV:21LX(1),35.4,85,10,1,5,40E-3,82.5,.33)
DISPLAY RANGE=CV:21L1CA
COMPUTE CV:21L1=OR(CV:21L1CA,CV:TMPO)
DELETE ENTRY=CV:21L1CA;CV:TMPO
DISPLAY RANGE=CV:21L1
PLOT Y-LABEL="GMS 21L1" TRACE(5)=CV:21L1 -
COMM      21L2 ZONE 2 (OVERREACHING) DISTANCE RELAY
COMPUTE CV:21L2AB=SD2H(CV:GVAB,CV:GIAB,CV:21LX(0),CV:21LX(1),123,85,10,1,5,40E-3,82.5,.33)
DELETE ENTRY=CV:GVAB
DISPLAY RANGE=CV:21L2AB
COMPUTE CV:21L2BC=SD2H(CV:GVBC,CV:GIBC,CV:21LX(0),CV:21LX(1),123,85,10,1,5,40E-3,82.5,.33)
DELETE ENTRY=CV:GVBC
DISPLAY RANGE=CV:21L2BC
COMPUTE CV:TMPO=OR(CV:21L2AB,CV:21L2BC)
DELETE ENTRY=CV:21L2AB;CV:21L2BC
COMPUTE CV:21L2CA=SD2H(CV:GVCA,CV:GICA,CV:21LX(0),CV:21LX(1),123,85,10,1,5,40E-3,82.5,.33)
DISPLAY RANGE=CV:21L2CA
COMPUTE CV:21L2=OR(CV:21L2CA,CV:TMPO)
DELETE ENTRY=CV:21L2CA;CV:TMPO;CV:GVCA;CV:GIAB;CV:GIBC;CV:GICA
DISPLAY RANGE=CV:21L2
PLOT Y-LABEL="GMS 21L2" TRACE(4)=CV:21L2 -
COMM      21L3 ZONE 3 (REVERSE BLOCKING) DISTANCE RELAY
COMM      NEGATE CURRENTS--21L3 CT IS REVERSE LOOKING
COMPUTE CV:IA=NEGATE(BC:GMS..A:5L1N.A)
COMPUTE CV:IB=NEGATE(BC:GMS..B:5L1N.B)
COMPUTE CV:IC=NEGATE(BC:GMS..C:5L1N.C)
COMM      LOAD ANGLE COMPENSATOR
COMPUTE CV:LACA=LAC(CV:IA,33.77)
COMPUTE CV:LACB=LAC(CV:IB,33.77)
COMPUTE CV:LACC=LAC(CV:IC,33.77)
COMPUTE CV:VA=ADD(NV:VT1N.A,CV:LACA)
COMPUTE CV:VB=ADD(NV:VT1N.B,CV:LACB)
COMPUTE CV:VC=ADD(NV:VT1N.C,CV:LACC)
DELETE ENTRY=CV:LACA;CV:LACB;CV:LACC
COMPUTE CV:VAB=SUBTRACT(CV:VA,CV:VB)
COMPUTE CV:VBC=SUBTRACT(CV:VB,CV:VC)
COMPUTE CV:VCA=SUBTRACT(CV:VC,CV:VA)
DELETE ENTRY=CV:VA;CV:VB;CV:VC
COMPUTE CV:IAB=SUBTRACT(CV:IA,CV:IB)
COMPUTE CV:IBC=SUBTRACT(CV:IB,CV:IC)
COMPUTE CV:ICA=SUBTRACT(CV:IC,CV:IA)
DELETE ENTRY=CV:IA;CV:IB;CV:IC
COMM      FILTER DROPOUT DELAY

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 26 (cont'd)

```
COMPUTE CV:FILTERX=TIMER(CV:21LX(0),0,60E-3)
DISPLAY RANGE=CV:FILTERX
COMPUTE CV:21L3AB=SD2H(CV:VAB,CV:IAB,CV:FILTERX,CV:21LX(1),160.7,87.1,10,1,5,0,82.5,.33)
DELETE ENTRY=CV:VAB;CV:IAB
DISPLAY RANGE=CV:21L3AB
COMPUTE CV:21L3BC=SD2H(CV:VBC,CV:IBC,CV:FILTERX,CV:21LX(1),160.7,87.1,10,1,5,0,82.5,.33)
DELETE ENTRY=CV:VBC;CV:IBC
DISPLAY RANGE=CV:21L3BC
COMPUTE CV:TMPO=OR(CV:21L3AB,CV:21L3BC)
DELETE ENTRY=CV:21L3AB;CV:21L3BC
COMPUTE CV:21L3CA=SD2H(CV:VCA,CV:ICA,CV:FILTERX,CV:21LX(1),160.7,87.1,10,1,5,0,82.5,.33)
DELETE ENTRY=CV:VCA;CV:ICA;CV:FILTERX;CV:21LX
DISPLAY RANGE=CV:21L3CA
COMPUTE CV:21L3=OR(CV:21L3CA,CV:TMPO)
DELETE ENTRY=CV:21L3CA;CV:TMPO
DISPLAY RANGE=CV:21L3
PLOT Y-LABEL="GMS 21L3" TRACE(3)=CV:21L3 -
COMM
COMM      DISTANCE SUPERVISION CURRENT RELAYS
COMM
COMPUTE CV:50LA=OVERCURRENT.IT(BC:GMS..A:5L1N.A,268,1,.33)
COMPUTE CV:50LB=OVERCURRENT.IT(BC:GMS..B:5L1N.B,268,1,.33)
COMPUTE CV:50LC=OVERCURRENT.IT(BC:GMS..C:5L1N.C,268,1,.33)
DISPLAY RANGE=CV:50LA;CV:50LB;CV:50LC
COMM      "OR" TO GET DISTANCE SUPERVISION OUTPUT
COMPUTE CV:TMPO=OR(CV:50LA,CV:50LB)
COMPUTE CV:50L=OR(CV:50LC,CV:TMPO)
DELETE ENTRY=CV:TMPO;CV:50LA;CV:50LB;CV:50LC
DISPLAY RANGE=CV:50L
PLOT Y-LABEL="GMS 50L" TRACE(6)=CV:50L RELEASE
COMM
COMM     "AND" TO GET PHASE-FAULT DIRECT TRIP
COMPUTE CV:PFDT=AND(CV:21L1,CV:50L)
DELETE ENTRY=CV:21L1
COMM     "AND" TO GET PHASE-FAULT PERMISSIVE TRIP
COMPUTE CV:PFPT=AND(CV:21L2,CV:50L)
DELETE ENTRY=CV:21L2
display range=cv:pfdt;CV:PFPT
COMM      "AND" TO GET PHASE REVERSE BLOCKING
COMPUTE CV:PRB=AND(CV:21L3,CV:50L)
DELETE ENTRY=CV:21L3;CV:50L
DISPLAY RANGE=CV:PRB
COMM
COMM      GROUND-FAULT RELAYS
COMM    COMPUTE 3 * ZERO-SEQUENCE VOLTAGE
COMPUTE CV:TMPO=ADD(NV:VT1N.A,NV:VT1N.B)
COMPUTE CV:TMP1=ADD(CV:TMPO,NV:VT1N.C)
COMM    FILTER 3VO FOR INPUT TO DIRECTIONAL ELEMENTS
COMPUTE CV:3VO=FILTER(CV:TMP1,1)
DELETE ENTRY=CV:TMPO;NV:VT1N.A;NV:VT1N.B;NV:VT1N.C;CV:TMP1
COMPUTE CV:PSFILTER=PS-FILTER.A(BC:GMS..A:5L1N.A,BC:GMS..B:5L1N.B,BC:GMS..C:5L1N.C)
DELETE ENTRY=BC:GMS..A:5L1N.A;BC:GMS..B:5L1N.B;BC:GMS..C:5L1N.C
COMM    FILTER 3IO FOR INPUT TO DIRECTIONAL ELEMENTS AND 50LN/IO...
COMPUTE CV:3IO=FILTER(CV:PSFILTER(1),1)
COMM    USE INSTANTANEOUS OVERCURRENT ELEMENT FOR FINITE SENSITIVITY
COMM        (NO HYSTERESIS WANTED HERE)

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 26 (cont'd)

```
COMPUTE CV:GATE=OVERCURRENT.IT(CV:3IO,50)
COMM    GATE 3IO
COMPUTE CV:G3IO=GATE(CV:3IO,CV:GATE)
COMPUTE CV:32R=DIRECTIONAL(CV:G3IO,CV:3VO,-89.5,96,.33)
COMM    NEGATE GATED 3IO FOR FORWARD ELEMENT
COMPUTE CV:NG3IO=NEGATE(CV:G3IO)
COMPUTE CV:32F=DIRECTIONAL(CV:NG3IO,CV:3VO,-89.5,85,.33)
DELETE ENTRY=CV:NG3IO;CV:3VO;CV:G3IO;CV:GATE
DISPLAY RANGE=CV:32F;CV:32R
PLOT HOLD Y-RANGE=(-19.9,19.9) Y-UNITS= -
PLOT Y-LABEL="GMS 32F" TRACE(2)=CV:32F -
PLOT Y-LABEL="GMS 32R" TRACE(1)=CV:32R -
COMM
COMM       GROUND INVERSE-TIME OVERCURRENT ELEMENT
COMPUTE CV:50LN1S=OVERCURRENT.IT(CV:PSFILTER(1),200,1000,.33)
DISPLAY RANGE=CV:50LN1S
PLOT Y-LABEL="GMS 50LN1S" TRACE(3)=CV:50LN1S -
COMM
COMM       "AND" TO GET DIRECTIONAL GROUND OVERCURRENT OUTPUT
COMPUTE CV:DGOC=AND(CV:32F,CV:50LN1S)
DISPLAY RANGE=CV:DGOC
DELETE ENTRY=CV:50LN1S
COMM
COMM       INSTANTANEOUS GROUND OVER-CURRENT RELAY
COMPUTE CV:RESTRAIN=COPY(CV:PSFILTER,0.2)
COMPUTE CV:50LNIOD=OVERCURRENT.R(CV:3IO,CV:RESTRAIN,1400,630,.33)
PLOT Y-LABEL="GMS 50LN/IOD" TRACE(6)=CV:50LNIOD -
COMPUTE CV:50LNIOH=OVERCURRENT.R(CV:3IO,CV:RESTRAIN,300,630,.33)
COMPUTE CV:50LNIOL=OVERCURRENT.R(CV:3IO,CV:RESTRAIN,100,630,.33)
DISPLAY RANGE=CV:50LNIOD;CV:50LNIOH;CV:50LNIOL
PLOT Y-LABEL="GMS 50LN/IOL" TRACE(4)=CV:50LNIOL -
PLOT Y-LABEL="GMS 50LN/IOH" TRACE(5)=CV:50LNIOH RELEASE
DELETE ENTRY=CV:PSFILTER;CV:RESTRAIN;CV:3IO
COMM
COMM       "OR" TO GET COMPLETE GROUND FAULT DIRECT TRIP OUTPUT
COMPUTE CV:GFDT=OR(CV:50LNIOD,CV:DGOC)
DISPLAY RANGE=CV:GFDT
DELETE ENTRY=CV:50LNIOD;CV:DGOC
COMM      "AND" TO GET GROUND FAULT PERMISSIVE TRIP
COMPUTE CV:GFPT=AND(CV:50LNIOH,CV:32F)
DELETE ENTRY=CV:50LNIOH;CV:32F
COMM      "AND" TO GET GROUND REVERSE BLOCKING
COMPUTE CV:GRB=AND(CV:50LNIOL,CV:32R)
DISPLAY RANGE=CV:GFPT;CV:GRB
DELETE ENTRY=CV:50LNIOL;CV:32R
PLOT HOLD Y-RANGE=(-19.9,19.9) Y-UNITS= -
PLOT Y-LABEL="GMS GROUND FAULT DIRECT TRIP" TRACE(5)=CV:GFDT -
PLOT Y-LABEL="GMS PHASE FAULT DIRECT TRIP" TRACE(6)=CV:PFDT -
PLOT Y-LABEL="GMS GROUND FAULT PERMISSIVE TRIP" TRACE(3)=CV:GFPT -
PLOT Y-LABEL="GMS PHASE FAULT PERMISSIVE TRIP" TRACE(4)=CV:PFPT -
PLOT Y-LABEL="GMS GROUND FAULT REVERSE BLOCKING" TRACE(1)=CV:GRB -
PLOT Y-LABEL="GMS PHASE FAULT REVERSE BLOCKING" TRACE(2)=CV:PRB
PLOT RELEASE
COMM
COMM      "OR" PHASE AND GROUND DIRECT TRIP TO GET DIRECT LOCAL TRIP
COMPUTE CV:GMSDLT=OR(CV:PFDT,CV:GFDT)

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 26 (cont'd)

```
DISPLAY RANGE=CV:GMSDLT
DELETE ENTRY=CV:PFDT;CV:GFDT
COMM     "OR" PHASE AND GROUND PERMISSIVE TRIP TO GET
COMM                COMBINED PERMISSIVE TRIP
COMPUTE CV:CPT=OR(CV:PFPT,CV:GFPT)
DISPLAY RANGE=CV:CPT
DELETE ENTRY=CV:PFPT;CV:GFPT
COMM     "OR" PHASE AND GROUND REVERSE BLOCKING TO GET REVERSE
COMM              BLOCKING
COMPUTE CV:RB=OR(CV:GRB,CV:PRB)
DISPLAY RANGE=CV:RB
DELETE ENTRY=CV:GRB;CV:PRB
COMM     USE DROP-OUT DELAY AND INVERSION TO GET "NO-REVERSE-BLOCKING"
COMPUTE CV:TMP=TIMER(CV:RB,0,100E-3)
DELETE ENTRY=CV:RB
COMPUTE CV:GMSNRB=NOT(CV:TMP)
DISPLAY RANGE=CV:GMSNRB
DELETE ENTRY=CV:TMP
COMM     "AND" PERMISSIVE ENABLE AND NO-REVERSE BLOCKING TO GET
COMM              LOCAL FORWARD PERMISSIVE
COMPUTE CV:GMSLFP=AND(CV:CPT,CV:GMSNRB)
PLOT TRACES/PAGE=4 HOLD Y-RANGE=(-19.9,19.9) Y-UNITS= -
PLOT Y-LABEL="GMS COMBINED PERMISSIVE TRIP" TRACE(1)=CV:CPT -
PLOT Y-LABEL="GMS NO REVERSE BLOCKING" TRACE(2)=CV:GMSNRB -
PLOT Y-LABEL="GMS LOCAL FORWARD PERMISSIVE" TRACE(3)=CV:GMSLFP -
PLOT Y-LABEL="GMS DIRECT LOCAL TRIP" TRACE(4)=CV:GMSDLT RELEASE
DELETE ENTRY=CV:CPT
DISPLAY RANGE=CV:GMSLFP
COMM
COMM     COMBINE WSN AND GMS SIGNALS IN PERMISSIVE TRIP BLOCK
COMM
COMPUTE CV:PERM=PERMISSIVE(CV:WSNLFP,CV:WSNDLT,CV:WSNNRB,CV:GMSLFP,CV:GMSDLT,CV:GMSNRB)
DISPLAY RANGE=CV:PERM(0);CV:PERM(1);CV:PERM(2);CV:PERM(3);CV:PERM(4);CV:PERM(5)
DISPLAY RANGE=CV:PERM(6);CV:PERM(7)
PLOT HOLD TRACES/PAGE=4 Y-RANGE=(-19.9,19.9) Y-UNITS= -
PLOT Y-LABEL="WSN PERMISSIVE TRIP TRANSMIT" TRACE(4)=CV:PERM(2) -
PLOT Y-LABEL="GMS PERMISSIVE TRIP TRANSMIT" TRACE(3)=CV:PERM(3) -
PLOT Y-LABEL="WSN REPEAT-IF-NO-BLOCK" TRACE(2)=CV:PERM(4) -
PLOT Y-LABEL="GMS REPEAT-IF-NO-BLOCK" TRACE(1)=CV:PERM(5) RELEASE
PLOT HOLD TRACES/PAGE=4 Y-RANGE=(-19.9,19.9) Y-UNITS= -
PLOT Y-LABEL="WSN TRANSFER TRIP TRANSMIT" TRACE(2)=CV:PERM(0) -
PLOT Y-LABEL="GMS TRANSFER TRIP TRANSMIT" TRACE(1)=CV:PERM(1) -
PLOT Y-LABEL="GMS CIRCUIT BREAKER TRIP" TRACE(3)=CV:PERM(7) -
PLOT Y-LABEL="WSN CIRCUIT BREAKER TRIP" TRACE(4)=CV:PERM(6) RELEASE
STOP
```

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.

Fig. 26 (cont'd)

The form of the function invocation in the TRP is:

COMPUTE **odsg**=AND(**idsg-1**,**idsg-2**)

where

odsg is the designator for the AND result,

idsg-1 is the designator for one input, and

idsg-2 is the designator for the second input.

2. DIRECTIONAL

The DIRECTIONAL function provides a model of a directional element based on a block-average phase comparator, with a transactor input to provide the adjustment for maximum torque angle (MTA). The MTA may be specified between 0 and about -89.5° (angles approaching -90° can cause numerical overflow during computation). For situations where the MTA is positive, so that the current leads the voltage, the current input must be negated. The negative of the actual MTA is then specified.

The form of the function invocation in the TRP is:

COMPUTE **odsg**=DIRECTIONAL(**Idsg**,**Vdsg**,**MTA**,**opzone**,**rhyst**,**gain**)

where

odsg is the designator for the output. This is a TRP waveform vector.

Element 0 is the relay (phase comparator) output. Element 1 is the output of the transactor, which is one of the phase comparator inputs (the other being the voltage).

Idsg is the designator for the input current.

Vdsg is the designator for the input voltage.

MTA is the designator for the maximum torque angle (angle of current for maximum relay operating tendency, using the voltage as reference), in degrees. The default value of the MTA is -45°.

opzone is the angular zone (in degrees) for which the relay will pick up, viz. the relay will operate if the angle of the current is **MTA±opzone** with respect to the voltage.

rhyst is the ratio of hysteresis to the full relay output range. Hysteresis here refers to the amount by which the comparator trip threshold exceeds the comparator reset threshold. Note that the hysteresis results in a "reset ratio" (ratio of input for reset to input for trip) of less than one for instantaneous (non-integrating) comparators. For integrating comparators, such as is used for this model, the reset ratio can be unity in spite of hysteresis, so that the effects of hysteresis may not be evident from steady-state testing. For the integrating comparator used here a value for **rhyst** of 1/3 results in trip and reset thresholds equally spaced between the relay output limits. This is usually the best arrangement for the prevention of chattering due to noise. The default value is zero, for no hysteresis.

gain is the integrator gain for the phase comparator. The default value is the maximum gain for correct operation under steady-state conditions (computed internally).

3. FILTER

The FILTER function simulates the operation of a simple RLC filter.

The form of the function invocation in the TRP is:

COMPUTE **odsg**=FILTER(**idsg**,**Q**,**F0**)

where

odsg is the designator for the filter output.

idsg is the designator for the filter input.

Q is the filter quality factor (circuit Q).

F0 is the frequency to which the filter is tuned, in Hertz (default value is power frequency)

4. LAC

The LAC function simulates the Westinghouse Canada LAC-1H load angle compensator used with the SD-2H reverse-reaching (zone 3) element 21L3.

The form of the function invocation in the TRP is:

COMPUTE **odsg**=LAC(**idsg**,**setting**,**Q**,**F0**)

where

odsg is the designator for the LAC output voltage.

idsg is the designator for the LAC input current.

setting is the LAC impedance setting (circuit gain at resonance).

Q is the LAC quality factor (circuit Q) at resonance (default 0.5).

F0 is the LAC resonance frequency, in Hertz (default value is power frequency).

5. NOT

The NOT function is performed as an NLR operation. The output is thus the algebraic negation of the input. This function is implemented as an alias of the TRP internal function NEGATE.

The form of the function invocation in the TRP is:

COMPUTE **odsg**=NOT(**idsg**)

where

odsg is the designator for the output.

idsg is the designator for the input.

6. OR

The OR function is performed as an NLR operation. The result is thus the algebraic maximum of the inputs. As for the AND function, this implementation permits only two inputs, although more could have been provided.† The function is implemented as an alias of the TRP internal function MAXIMUM.

The form of the function invocation in the TRP is:

COMPUTE **odsg**=OR(**idsg-1**,**idsg-2**)

where

odsg is the designator for the OR output.

idsg-1 is the designator for one input.

idsg-2 is the designator for the second input.

7. OVERCURRENT.IT

The OVERCURRENT.IT function simulates an inverse-time overcurrent relay. The nominal relay operating time (in seconds) is given by

$$t = 0.661\ TMS/(i-1)$$

where i is the RMS input current as a multiple of the relay setting and **TMS** is the time-multiplier setting (with a minimum value of one). (The curve

†Multiple two-input OR functions can easily be cascaded to produce a multiple-input OR function.

represented by this equation corresponds to the time-overcurrent curve supplied by relay manufacturers.) In use, the value of TMS would be selected to best approximate the time-overcurrent curve for the relay being modelled.

The OVERCURRENT.IT function may also be used to simulate an instantaneous overcurrent relay by specifying a TMS value of one, which gives the highest possible speed for correct operation under steady-state conditions.

The form of the function invocation in the TRP is:

COMPUTE **odsg**=OVERCURRENT.IT(**idsg**,**setting**,**TMS**,**rhyst**)

where

odsg is the designator for the output.

idsg is the designator for the input current.

setting is the relay pickup setting.

TMS is the relay time multiplier setting (default is one)

rhyst is the ratio of hysteresis to the full relay output range, as for the DIRECTIONAL function. The default value is zero, for no hysteresis.

8. OVERCURRENT.R

The OVERCURRENT.R function simulates a restrained instantaneous overcurrent relay. The relay operates when the difference between the average operating and restraining currents exceeds the setting.

This model is used with the positive-sequence filter model PS-FILTER.A and the RLC filter model FILTER to simulate the operation of a Westinghouse Canada type S1G-1H positive-sequence-restrained ground overcurrent relay. The S1G-1H design is different from that of the model used here. The S1G-1H uses a phase-shifting network, three-phase bridge rectifier, and RC filter network to obtain a DC level proportional to the positive sequence restraint. This level is augmented by the setting; the combination forms a bias which offsets the rectified zero-sequence operating current. The offset zero-sequence quantity is then applied to an instantaneous level detector, which operates when the offset zero-sequence quantity exceeds a threshold. More information can be found in the manufacturer's instruction manual (Westinghouse, 1968).

Details of the model are given in part C, section 10 of this appendix. Differences between the operating details are bound to result in small differences in the transient behaviour.

The form of the function invocation in the TRP is:

COMPUTE **odsg**=OVERCURRENT.R(**idsg-o**,**idsg-r**,**setting**,**maxar**,**rhyst**)

where

odsg is the designator for the output.

idsg-o is the designator for the operating current.

idsg-r is the designator for the restraining current.

setting is the difference between the RMS values of the operating and restraining currents which barely causes the relay to pick up.

maxar is the maximum RMS amplitude for the restraining quantity. This value determines the relay gain. For correct operation, the value must be larger than the maximum possible RMS restraining current under steady-state conditions.

rhyst is the ratio of hysteresis to the full relay output range, as described for the DIRECTIONAL function. The default value is zero, for no hysteresis.

9. PERMISSIVE

The PERMISSIVE function simulates the permissive- (and transfer-) trip logic for the Peace River protection. The modelling used requires the transfer- and permissive-trip signals to be low ("off" state) before the start of the simulation. All logical operations are performed as NLR operations. The operations involved are shown in figs. 11, 12, and 13.

The form of the function invocation in the TRP is:

COMPUTE **od**=PERMISSIVE(**lfpa,dlta,nrba,lfpb,dltb,nrbb,pd,pud1,dd1,pud2,dd2**)

where

od is the designator for the output, which is a TRP waveform vector. Elements 0 and 1 are the transfer-trip signals for ends A and B, respectively. Elements 2 and 3 are the permissive-trip transmit signals for ends A and B, respectively. Elements 4 and 5 are the repeat-if-no-block signals for ends A and B, respectively. Elements 6 and 7 are the circuit-breaker trip signals for ends A and B, respectively.

lfpa and **lfpb** are the local forward permissive signals for ends A and B, respectively.

dlta and **dltb** are the direct local trip signals for ends A and B, respectively.

nrba and **nrbb** are the no-reverse-blocking signals for ends A and B, respectively.

pd is the propagation delay of the communications channels. The delay is the same for both transfer- and permissive-trip channels. The default value is 9 ms.

pud1 and **dd1** are the pickup and dropout delays, respectively, for the first (start) repeat-if-no-block timer. The defaults are 55 and 100 ms, respectively.

pud2 and **dd2** are the pickup and dropout delays, respectively, for the second (stop) repeat-if-no-block timer. The defaults are 45 and 20 ms, respectively.

10. PS-FILTER.A

The PS-FILTER.A function simulates the positive sequence filter used in 50LN, which is shown in the Westinghouse T&D Book (Westinghouse, 1964, fig. 31h, pg. 374). Residual current output ($3I_0$) is also available from this filter.

The form of the function invocation in the TRP is:

COMPUTE **odsg**=PS-FILTER.A(**dsg-**$\mathbf{I_A}$,**dsg-**$\mathbf{I_B}$,**dsg-**$\mathbf{I_C}$)

where

odsg is the designator for the output. This is a TRP waveform vector, for which element 0 is the positive-sequence filter output, and element 1 is the residual current ($3I_0$) output.

dsg-$\mathbf{I_A}$, **dsg-**$\mathbf{I_B}$, and **dsg-**$\mathbf{I_C}$ are the designators of the three phase currents in phase-sequence order.

11. SDX1H

The SDX1H function is a model of the Westinghouse Canada fault-detecting relay SDX-1H.

The form of the function invocation in the TRP is:

COMPUTE **odsg**=SDX1H(**dsg-**$\mathbf{V_A}$,**dsg-**$\mathbf{V_B}$,**dsg-**$\mathbf{V_C}$,**uvset,nsset,uvrh,nsrh,nsfq**)

where

odsg is the designator for the output, which is a TRP waveform vector. Element 0 is the signal for controlling the SD-2H filter Q. Element 1 is the signal for controlling the insertion of the pickup delay in 21L1 and 21L2. Element 2 is the output of the undervoltage relay internal to the SDX-1H. Element 3 is the output of the negative sequence relay internal to the SDX-1H. (The TRP also creates and automatically deletes a fifth element, which is used for temporary storage.)

dsg-V$_{\mathbf{A}}$, **dsg-V**$_{\mathbf{B}}$, and **dsg-V**$_{\mathbf{C}}$ are the designators for the three phase voltages in phase sequence order.

uvset is the setting for the undervoltage relay.

nsset is the setting for the negative-sequence relay.

uvrh and **nsrh** are the hysteresis ratios (as for the DIRECTIONAL function) for the undervoltage and negative-sequence relays, respectively. The default values are zero, for no hysteresis.

nsfq is the circuit Q of the memory portion of the negative sequence filter. The default value is one.

12. SD2H

The SD2H function is a model of the Westinghouse Canada type SD-2H memory-polarized mho relay. Note that whereas the actual relay uses a block-instantaneous (diode ring modulator) phase comparator, this model uses a block-average phase comparator. Some difference in the transient behaviour can thus be expected.

The form of the function invocation in the TRP is:

COMPUTE **odsg**=SD2H(**idV,idI,idS,idD,zc,azc,qh,ql,qm,dly,gam,rh,gf,f0**)

where

odsg is the designator for the output, which is a TRP waveform vector. Element 0 is the relay output. Element 1 is the phase-comparator output without the additional pickup delay. Element 2 is the IZ-V input to the phase comparator. Element 3 is the polarizing voltage (memory output) input to the phase comparator.

idV is the designator for the input voltage.

idI is the designator for the input current.

idS is the designator for the filter-switching control input.

idD is the designator for the pickup-delay-insertion control input.

zc is the magnitude of the impedance setting in ohms.

azc is the angle of the impedance setting in degrees.

qh is the high-Q value for the IZ-V input filter.

ql is the low-Q value for the IZ-V input filter.

qm is the value of the memory Q.

dly is the pickup delay inserted when the pickup-delay-insertion control input is positive.

gam is the phase difference (in degrees) which the phase comparator will accept as phase coincidence. The default value is 90°, which produces the usual circular mho characteristic.

rh is the ratio of hysteresis to the full relay output range, as described for the DIRECTIONAL function. The default value is zero, for no hysteresis.

f0 is the frequency to which the input circuitry is tuned, in Hertz. The default value is the power system frequency.

13. TIMER

The TIMER function simulates the operation of a delayed-pickup/delayed-dropout timer. The output is compatible with NLR.

The form of the function invocation in the TRP is:

COMPUTE **odsg**=TIMER(**idsgC**,**pudly**,**dodly**,**ic**)

where

odsg is the designator for the output.

idsgC is the designator for the timer control input. The timer begins timing the pickup delay when this signal goes high, and begins timing the dropout delay when it goes low. The timer resets immediately (i.e. the timing cycle aborts) if the control signal returns low before the timer picks up, or returns high before the timer drops out.

pudly is the pickup delay in seconds (default zero).

dodly is the dropout delay in seconds (default zero).

ic is the timer initial condition. Any positive value causes the timer to be initialized to a high state; a negative value causes the timer to be initialized to a low state, which is the default. A value of zero is illegal.

C. RELAY MODELLING DETAILS

This section gives details of the relay modelling which forms the basis for the TRP user functions described in the previous section. All models are written as self-contained, stand-alone FORTRAN subroutines. As the relay modelling was secondary to the main thrust of this research, certain details have been left out where the complexity of the derivation was not justified by the importance of the details.

1. Assumptions

The following assumptions and comments apply to the relay modelling for this project:

- In all cases, relay sensitivity is assumed to be essentially infinite—that is, the input quantities are not required to exceed threshold values before the relay will operate (apart from any thresholds intrinsic to the relaying function, such as the input current trip setting for an overcurrent relay, for example).

- The time base of the input data is to have a constant step size.

- Wherever possible, generic relay models are employed.

- All models are self-contained. Inputs and outputs are considered to be fully bufferred—source impedances are assumed to be zero, load impedances are assumed to be infinite. All input and output loading effects have therefore either been incorporated into the models, or ignored.

- All relays use an output compatible with NLR. Figure 2 shows a hardware-equivalent method of obtaining this output for a static relay.

2. Model Initialization

Each model is initialized as the first step when it is invoked. All models are assumed to be initially in steady state. The first two time-steps of input quantities are assumed† to come from a steady-state cosine function at power frequency (ω_s) of the form

$$\text{input}(t) = \text{magnitude}\cdot\cos(\omega_s t + \text{angle})$$

where magnitude and angle are obtained in the following manner:

Assume:

$$f_1 = \text{magnitude}\cdot\cos(\omega_s t_1 + \text{angle})$$

†In use, the first two steps of the input quantities must occur before any power system disturbance. This is generally convenient when doing digital power system simulations using, for example, the BPA EMTP. In the event that the first two steps do not correspond to a pure power-frequency sinusoid, there will be some error in initialization, causing a transient response in the relay model at the start of the simulation.

$$f_2 = \text{magnitude} \cdot \cos(\omega_s t_2 + \text{angle})$$

Expanding the cosine terms and expressing the equations in matrix form:

$$\begin{bmatrix} f_1 \\ f_2 \end{bmatrix} = \begin{bmatrix} \cos \omega_s t_1 & \sin \omega_s t_1 \\ \cos \omega_s t_2 & \sin \omega_s t_2 \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix}$$

where

$$a = \text{magnitude} \cdot \cos(\text{angle})$$

$$b = -\text{magnitude} \cdot \sin(\text{angle})$$

Now solving for a and b

$$a = (f_1 \sin \omega_s t_2 - f_2 \sin \omega_s t_1) \,/\, \det$$

$$b = (f_2 \cos \omega_s t_1 - f_1 \cos \omega_s t_2) \,/\, \det$$

where

$$\det = \cos \omega_s t_1 \sin \omega_s t_2 - \cos \omega_s t_2 \sin \omega_s t_1$$

It is now possible to solve for magnitude and angle, since

$$\frac{b}{a} = -\tan(\text{angle})$$

$$(a^2 + b^2)^{1/2} = \text{magnitude}$$

3. Accounting for Finite Sensitivity

There are several methods which can be used to account for finite relay sensitivity where this is an important factor in the operation of the protection scheme. One method is to AND the output of the "infinite" sensitivity relay with the output of an instantaneous low-set element (current or voltage, as appropriate) which picks up at the sensitivity limit. Typically one low-set element would be used for each input with a significant input sensitivity. One disadvantage of this scheme is that extra simulation is involved for the low-set elements and the AND combination. A more serious disadvantage is that the technique can lead to apparent misoperation due to the reset time of the principal relay (since it can pick up on inputs below the sensitivity limit).

A second method of accounting for finite sensitivity is to use low-set elements as just described to "gate" the input to the principal relay. The objective here is to produce a non-zero output from the gate (equal to the input) only when the low-set element has picked up. This is similar to conventional practice with electromagnetic directional overcurrent relays, where torque is produced in the principal (overcurrent) element only when the modulating (directional) element has picked up. While additional simulation (for the low-set elements and the gate) is also required with this method, there is no longer a problem with pickup or reset delays caused by input below the sensitivity threshold.

A third method of accounting for finite sensitivity is by incorporating the sensitivity-limiting detail directly into the relay model. This is clearly the most accurate of the three methods, but is applicable only for models of specific relays, and where schematic diagrams and component details are available. Due to the high cost of software development, the advantages of this method will seldom be sufficient to justify its use for applications studies.

A fourth method of accounting for the effects of finite sensitivity is to treat the input sensitivity as a hard threshold—the instantaneous value of the input quantity is considered to be zero unless it exceeds the specified threshold. Values exceeding the threshold will either be left unchanged (similar to the second method), or be reduced by the threshold level (probably the more realistic choice for semiconductor relays). An expression which produces the latter effect is

$$x' = \max(x-t,0) + \min(x+t,0)$$

where

t is the threshold (> 0),

x is the input quantity, and

x' is the input quantity modified for finite sensitivity.

The fourth method probably offers the best compromise between realism and efficiency.

4. Solving State Equations using Central Differences

The general form of the state equations is

$$D\dot{y} = Ay + Bu + C\dot{u}$$

where

y is the vector of state variables,

$\dot{y}$ is the time-derivative of y,

u is the vector of inputs,

$\dot{u}$ is the time-derivative of u, and

A, B, C, and D are matricies.

Writing this as a central difference equation:

$$D\left(\frac{y^k - y^{k-1}}{\Delta t}\right) = A\left(\frac{y^k + y^{k-1}}{2}\right) + B\left(\frac{u^k + u^{k-1}}{2}\right) + C\left(\frac{u^k - u^{k-1}}{\Delta t}\right)$$

Collecting the y^k terms on the left and all other terms on the right and solving for y^k gives:

$$y^k = Ey^{k-1} + Fu^k - Gu^{k-1}$$

where

$$E = \left(\frac{2D}{\Delta t} - A\right)^{-1}\left(\frac{2D}{\Delta t} + A\right)$$

$$F = \left(\frac{2D}{\Delta t} - A\right)^{-1}\left(\frac{2C}{\Delta t} + B\right)$$

$$G = \left(\frac{2D}{\Delta t} - A\right)^{-1}\left(\frac{2C}{\Delta t} - B\right)$$

5. Directional Element Modelling

The directional element is implemented using the block-average phase comparator model and the transactor model (see sections 6 and 7, following). The phase comparator inputs are

$$S_A = IZ$$

$$S_B = V$$

where the impedance Z is selected to get the required maximum torque angle (MTA). Input S_B is the voltage input to the directional element. Input S_A is obtained from the output of the transactor model. The transactor input is the current input to the directional element. The transactor is set to provide mimic impedance Z.

The MTA is the difference between the angle of the current and the angle of the voltage when S_A and S_B are in phase. Thus

$$\begin{aligned} \text{MTA} &= \arg(I) - \arg(V) \\ &= \arg(I) - \arg(IZ) \\ &= \arg(I) - (\arg(I) + \arg(Z)) \\ &= -\arg(Z) \end{aligned}$$

where $\arg(I)$ is the angle of I, etc.

The MTA is thus controlled by the transactor mimic impedance, and may range from zero to nearly -90°. (The latter limit must be excluded so that numerical difficulties do not arise as a consequence of extremely small values of R in the transactor model.)

6. Transactor Modelling

a. *Circuit*

The transactor is modelled as a parallel combination of the magnetizing inductance and a load resistance (fig. 27). The output is taken as the current in the resistance. Where the voltage across the resistance is required, the output current can be multiplied by a factor equal to R.

b. *Derivation of the differential equations*

The differential equations describing the transactor circuit are:

$$v_R = Ri_{out}$$

$$= L\dot{i}_L$$

$$i_{in} = i_{out} + i_L$$

where the variables are identified in fig. 27.

Eliminating v_R, and expressing i_L in terms of i_{in} and i_{out}:

$$Ri_{out} = L(\dot{i}_{in} - \dot{i}_{out})$$

In standard form (section 4) this becomes

$$D\dot{y} = Ay + Bu + C\dot{u}$$

where

$$y = i_{out}$$

$$u = i_{in}$$

$$D = L$$

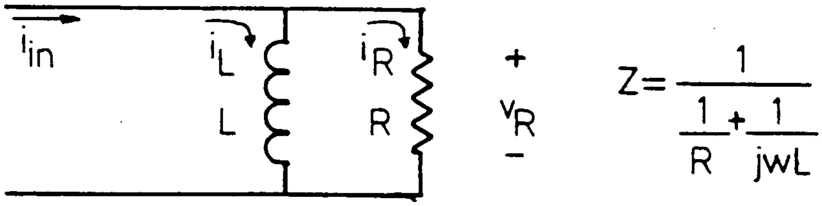


Fig. 27. Transactor equivalent circuit

$$A = -R$$

$$B = 0$$

$$C = L$$

c. *Equations as programmed*

The differential equation derived earlier is programmed using central differences, as described in section 4. The transition equation is, in standard form,

$$y^k = E\, y^{k-1} + F\, u^k - G\, u^{k-1}$$

and the matricies E, F, and G are

$$E = \left(\frac{2L}{\Delta tR}+1\right)^{-1}\left(\frac{2L}{\Delta tR}-1\right)$$

$$F = \left(\frac{2L}{\Delta tR}+1\right)^{-1}\frac{2L}{\Delta tR}$$

$$G = F$$

d. Initialization

Initial values are required for i_{in} and i_{out}. By assumption,

$$i_{in}(t) = \hat{I}_{in} \cos(\omega_s t + \theta_{in})$$

where $\hat{I}_{in}$ and θ_{in} are found as described in section 2.

The phasor I_{out} may be found from the phasor I_{in} by current-divider action:

$$I_{out} = \frac{j\omega L}{R + j\omega L} I_{in}$$

$$= H\ I_{in}$$

Thus

$$i_{out}(t) = \hat{I}_{OUT} \cos(\omega_s t + \theta_{out})$$

where

$$\hat{I}_{OUT} = |H|\ \hat{I}_{in}$$

$$\theta_{out} = \arg(H) + \theta_{in}$$

The initial values can now be computed directly.

7. Block-average Phase Comparator Model

a. Circuit

The block-average phase comparator is modelled as a polarity coincidence circuit (performing a Boolean NOR), the output of which is offset by a setting-dependent bias and integrated between two output limits.

b. Equations as programmed

The coincidence circuit is modelled with the following logic:

```
IF ((S1(I).GT.0. .AND.  S2(I).GT.0.) .OR.
    (S1(I).LT.0. .AND.  S2(I).LT.0.))  THEN

INPUT=(1.-bias)

ELSE

INPUT=-bias

END IF
```

The use of the .GT. and .LT. rather than .GE. and .LE. ensures that the comparator will not produce an output if either input is zero. The value bias is the bias current for the integrator, used to determine the phase angle spread (between the two inputs) for which the comparator will produce an output (this is the comparator "setting"). The value of bias may be computed from

$$\text{bias} = 1 - \gamma/180$$

where γ (in degrees) is the phase angle spread (between inputs) for which the comparator must produce an output (the phase angle spread corresponding to an "in-phase" comparison).

The integration is performed using trapezoidal integration

$$\text{output}(k) = \text{output}(k-1) + \text{gain}\cdot(\text{input}(k)+\text{input}(k-1))\cdot\frac{\Delta t}{2}$$

where gain is the integrator gain, and Δt is the time step.

The value of output is constrained to lie within preset limits.

c. *Initialization*

Initial values are required for both input signals and the integrator output voltage. The input signals are described by

$$S_1(t) = A_1\cos(\omega_s t+\theta_1)$$

$$= A_1\cos a$$

$$S_2(t) = A_2 \cos(\omega_s t+\theta_2)$$

$$= A_2 \cos(a+\delta a)$$

where $\delta a = \theta_2-\theta_1$. The values of A_1, A_2, θ_1, and θ_2 are obtained as described in section 2.

The integrator output voltage can be found by computing the amount by which the output has integrated away from one of the output voltage limits. Since the initial conditions are taken from a steady-state condition, the comparator must initially be stable in either a high or low state. Which of these states the comparator is in can be determined from the phase difference between the steady-state values of the two input signals, and will determine which of the two voltage limits the integrator is working from.

From knowledge of the comparator state, it is also possible to determine the instant at which the integrator will leave the limit and enter the linear region (first instant of polarity non-coincidence for comparator in high state, first instant of polarity coincidence for comparator in low state).

This is the approach which will be used to derive initializing equations for the integrator output.

Since the phase comparator is symmetrical with respect to the two inputs, for convenience designate S_1 and S_2 such that $\delta a > 0$. (The case for $\delta a = 0$ is trivial, since the comparator would then be constantly at the high limit F_{max}).

The inputs to the phase comparator now have the appearance shown in fig. 28, where the shaded regions indicate the zones of phase coincidence, a_x is the value of a at which the phase coincidence terminates, and a_y is the value of a at which the phase coincidence begins.

Note that the integrator input will be 1 + bias from a_y to a_x and bias from a_x to $a_y + \pi$. The integrator will accumulate if the average input is positive, viz.

$$(1-\text{bias})(a_x - a_y) - \text{bias}(a_y + \pi - a_x) > 0$$

so that, collecting terms and solving for bias

$$\text{bias} < (a_x - a_y)/\pi$$

But $(a_x - a_y) = \pi - \delta a$, so the phase comparator output will be true when

$$\text{bias} < 1 - da/\pi$$

and so

$$\text{bias} = 1 - \text{setting}/\pi$$

where the setting is the maximum value of phase difference, in radians, for

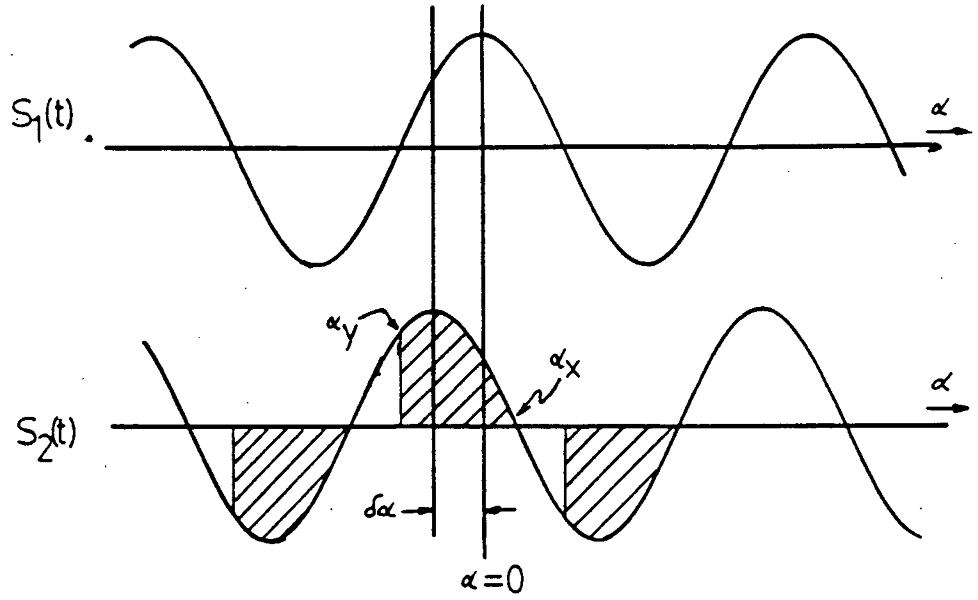


Fig. 28. Input waveforms for phase comparator derivations

which coincidence is detected.

Now in the case where δa < setting, the comparator will be in the "true" state, and the integrator output at a_0 (the initial value of a) will be (taking advantage of the half-cycle symmetry)

for $a_y \leq a_0 \leq a_x$

$$\text{output}(a_0) = F_{max} + \text{gain}\{\text{bias}(\pi - a_y - a_x) + (a_0 - a_y)(1 - \text{bias})\}/\omega_s$$

for $a_x \leq a_0 \leq a_y + \pi$

$$\text{output}(a_0) = F_{max} - \text{gain} \cdot \text{bias}(a_0 - a_x)/\omega_s$$

while in the case where δa > setting, the comparator will be in the "false" state, and the integrator output at a_0 will be

for $a_y \le a_0 \le a_x$

$$\text{output}(a_0) = F_{min} + \text{gain}(1-\text{bias})(a_0 - a_y)/\omega_s$$

for $a_x \le a_0 \le a_y + \pi$

$$\text{output}(a_0) = F_{min} + \text{gain}\{(1-\text{bias})(a_x - a_y) - \text{bias}(a_0 - a_x)\}/\omega_s$$

where F_{min} is the minimum integrator output limit, and F_{max} is the maximum integrator output limit. Note that for $-\frac{\pi}{2} \le a_0 \le \frac{\pi}{2}$, $a_y = -\frac{\pi}{2}$ and $a_x = \frac{\pi}{2} - \delta a$.

8. Filter/Memory Circuit Modelling

The memory and RLC filter circuits are identical, and so use the same model. There are essentially two possible configurations of the circuit: series RLC with voltage drive, and parallel RLC with current drive. Two other equivalent configurations can be obtained by converting the voltage source to a Norton equivalent source, and the current source to a Thevenin equivalent source. The series RLC with voltage drive and parallel RLC with current drive configurations produce identical equations. Only the series RLC configuration will, therefore, be described here.

a. Circuit

The filter consists of a series combination of R, L, and C, with a voltage drive (fig. 29). The output may be either i or

$$v_r = k \cdot Ri,$$

where $0 < k \leq 1$. The gain at resonance ($\omega = \omega_0$) will be R^{-1} in the first case, and k in the second case. In both cases,

$$\text{output} = \text{gain} \cdot Ri$$

b. Derivation of the state equations

The differential equations describing the filter circuit are

$$v = L\dot{i} + v_C + Ri$$

$$i = C\dot{v}_C$$

where the variables are identified in fig. 29.

Let g=circuit gain, o=output, u=input=v, and y_2=state variable=v_C. The circuit Q is

$$Q = \omega_0 L/R$$

where ω_0 is the resonance frequency, given by

$$\omega_0 = (LC)^{-1/2}$$

(For the current driven parallel RLC configuration, using $u=i$, $y_2=i_L$, and $Q=\omega_0 CR$ will produce results identical to the following.)

It follows that

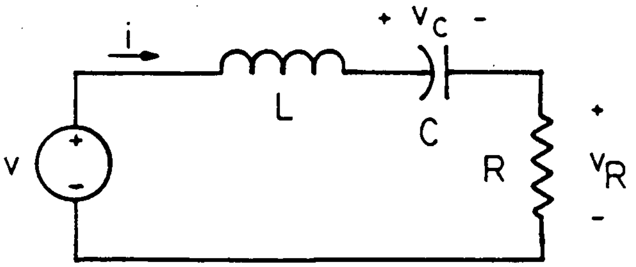


Fig. 29. Series RLC filter equivalent circuit

$$L = RQ/\omega_o$$

$$C = (\omega_o{}^2 L)^{-1} = (\omega_o RQ)^{-1}$$

Substituting into the differential equations

$$u = \frac{Q}{g\omega_o}\dot{o} + y_2 + \frac{o}{g}$$

$$\frac{o}{g} = \frac{1}{\omega_o Q}\dot{y}_2$$

Letting $y_1 = o/g$ be the normalized output

$$u = \frac{Q}{\omega_o}\dot{y}_1 + y_1 + y_2$$

$$y_1 = \frac{1}{\omega_o Q}\dot{y}_2$$

In standard form (section 4) these become

$$D\dot{y} = Ay + Bu + C\dot{u}$$

where

$$D = \begin{bmatrix} \dfrac{Q}{\omega_o} & 0 \\ 0 & \dfrac{1}{\omega_o Q} \end{bmatrix}$$

$$A = \begin{bmatrix} -1 & -1 \\ 1 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$C = \overline{0}$$

c. *Equations as programmed*

The differential equations derived earlier are programmed using central differences, as described in section 4. The transition equation is, in standard form,

$$y^k = Ey^{k-1} + Fu^k - Gu^{k-1}$$

where the matricies **E**, **F**, and **G** are

$$E = \frac{1}{\det} \begin{bmatrix} -1 - \dfrac{1}{C_1 Q} + \dfrac{1}{C_1^2} & -\dfrac{2}{QC_1} \\ \dfrac{2Q}{C_1} & -1 + \dfrac{1}{C_1 Q} + \dfrac{1}{C_1^2} \end{bmatrix}$$

$$F = \frac{1}{\det} \begin{bmatrix} \dfrac{1}{C_1 Q} \\ 1 \end{bmatrix}$$

$$G = -F$$

where

$$C_1 = \frac{\omega_0 \Delta t}{2}$$

$$\det = 1 + \frac{1}{C_1 Q} + \frac{1}{C_1^2}$$

d. Initialization

Initialization will be at power frequency ($\omega = \omega_s$). Initial values are required for the input, the output, and the state variable. The derivations which follow are for the generalized state equations, and so produce identical results for both series and parallel RLC configurations.

The input is described by

$$u(t_0) = \hat{U} \cos(\omega_s t_0 + \theta_u)$$

where $\hat{U}$ and θ_u are found as described in section 2.

The phasor equations may be found from the state equations:

$$U = j\omega_s Y_1 \frac{Q}{\omega_0} + Y_1 + Y_2$$

$$Y_1 = j\omega_s Y_2 \frac{1}{\omega_0 Q}$$

Let $\Omega = \omega_s / \omega_0$, and using the second equation to substitute for Y_2 in the first:

$$U = Y_1 (j\Omega Q + 1 + \frac{Q}{j\Omega})$$

which implies

$$Y_1 = \frac{j\Omega}{(1-\Omega^2)Q+j\Omega} U$$

Now using the second state equation

$$Y_2 = \frac{Q}{j\Omega} Y_1 = \frac{Q}{(1-\Omega^2)Q+j\Omega} U$$

9. Inverse-Time Overcurrent Model

The inverse-time overcurrent model is essentially a single-input amplitude comparator, and may be used as such with an appropriate input quantity and setting. The nominal operating time (in seconds) is given by

$$t = 0.661 \frac{TMS}{(i-1)}$$

where TMS is the time multiplier setting, with a minimum value of one, and i is the RMS input current as a multiple of setting.

The curve described by this equation corresponds to the time-overcurrent curves provided by manufacturers for their relays. The value of TMS is selected to match, as closely as possible, the curve of the model to the curve of the actual relay. With TMS = 1 the model operates at maximum speed, and can be used to simulate "instantaneous" elements (e.g. overcurrent, overvoltage, etc.).

a. Circuit

The comparator design on which this model is based consists of a full-wave rectifier, the output of which is offset by a setting-dependent bias and integrated between two output limits. The comparator thus operates on the average value of the input quantity. For the inverse-time overcurrent relay, the input is the current being monitored.

b. Equations as programmed

The output is computed from trapezoidal integration of |i(t)| - bias:

$$\text{output}(k) = \text{output}(k-1) + \text{gain}(|i(k)|+|i(k-1)|-2\cdot\text{bias})\cdot\frac{\Delta t}{2}$$

where gain is the integrator gain, and Δt is the time step.

The value of gain is the maximum comparator gain (see subsection (d) following) divided by the value of TMS. Operating speed is thus inversely proportional to TMS, and is highest for TMS = 1.

The value of output is constrained to lie within two range limits.

c. Initialization

Initial values are required for the input signal and the integrator output voltage. The input signal is described by

$$s(t) = A\cos(\omega_s t + \theta)$$

where the values of **A** and θ are obtained as described in section 2.

The approach used to derive initializing equations for the integrator output is similar to that used for the block-average phase comparator. From knowledge of the comparator state, it is possible to determine the instant at which the integrator will leave the limit and enter the linear region. This will occur at the first instant at which the bias exceeds the rectified input if the comparator is in the high state, and the first instant at which the rectified input exceeds the bias if the comparator is in the low state.

Define an angle α such that

$$\alpha = \omega_s t + \theta$$

and

$$s(t) = A \cos \alpha .$$

The integrand has the appearance shown in fig. 30, where

$\alpha = \omega_s t + \theta$

α_n = value of α at which integrand becomes negative

α_p = value of α at which integrand becomes positive.

Note that α_n and α_p both satisfy

$$|A \cos \alpha_n| = |A \cos \alpha_p| = \text{bias}.$$

If $\cos \alpha_0 > 0$ where α_0 is the initial value of α, normalized such that

$$-\frac{\pi}{2} \le \alpha_0 < 3\frac{\pi}{2},$$

then the equations are

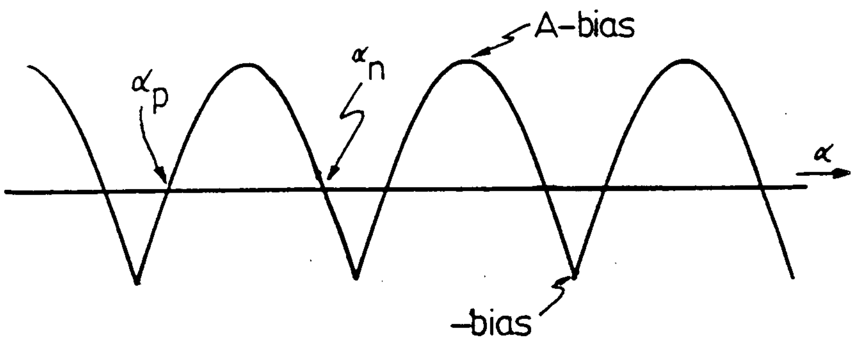


Fig. 30. Input waveforms for amplitude comparator derivations

$$|A|\cos a_n' = |A|\cos a_p' = \text{bias}$$

so

$$a_n' = \arccos \frac{\text{bias}}{|A|}$$

$$a_p' = -a_n'$$

and let $a_0' = a_0$.

Otherwise

$$|A|\cos a_n'' = |A|\cos a_p'' = -\text{bias}$$

so

$$a_n'' = \pi + \arccos \frac{\text{bias}}{|A|} = \pi + a_n'$$

$$a_p'' = \pi - \arccos \frac{\text{bias}}{|A|} = \pi - a_n'$$

and let $a_0'' = a_0 = a_0' + \pi$.

In the case where the relay is in the trip state:

$$|A| > \sqrt{2}\ \text{setting} = \frac{\pi}{2}\cdot\text{bias}.$$

If $a_n' < a_0' \le \frac{\pi}{2}$ then

$$\text{output} = F_{max} + \frac{\text{gain}}{\omega_s}\{|A|(\sin a_0' - \sin a_n') - \text{bias}(a_0'-a_n')\}$$

otherwise

$$\text{output} = F_{max} + \frac{\text{gain}}{\omega_s}\{|A|(2+\sin a_0' - \sin a_n') - \text{bias}(\pi+a_0'-a_n')\}$$

In the case where the relay is in the reset state:

$$|A| < \sqrt{2}\ \text{setting} = \frac{\pi}{2}\cdot\text{bias}.$$

If $a_p' < a_0' < \frac{\pi}{2}$ then

$$\text{output} = F_{min} + \frac{\text{gain}}{\omega_s}\{|A|(\sin a_0' - \sin a_p') - \text{bias}(a_0'-a_p')\}$$

otherwise

$$\text{output} = F_{min} + \frac{\text{gain}}{\omega_s}\{|A|(2+\sin a_0' - \sin a_p') - \text{bias}(\pi+a_0'-a_p')\}$$

d. Computation of maximum comparator gain

The maximum value of comparator gain is limited by the ripple in the comparator output. The ripple will be a maximum for a steady-state input just below setting. The maximum gain will be just large enough so that the comparator nearly operates for maximum ripple.

Assuming symmetry between the trip and reset thresholds (the usual case), the peak integrator ripple at setting will be at $a_0'=a_n'$ for the reset-state equations derived in the previous section, so that

$$\text{peak output} = F_{min} + \frac{\text{gain}}{\omega_s}\{|A|(\sin a_n' - \sin a_p') - \text{bias}(a_n' - a_p')\}$$

For an input equal to the setting

$$a_p' = -a_n' = -\arccos\frac{\text{bias}}{|A|}$$

$$= -\arccos\frac{2}{\pi}$$

so the peak output is

$$F_{min} + 0.2105(2\sqrt{2}\,\frac{\text{gain}}{\omega_s}\cdot\text{setting}).$$

The maximum gain will produce a peak output just equal to the threshold. For a threshold of F_T, the maximum gain is

$$1.679\ \omega_s\ \frac{(F_T - F_{min})}{\text{setting}}$$

10. Positive-Sequence-Restrained Overcurrent Relay

The positive-sequence-restrained overcurrent relay is essentially a double-input amplitude comparator. The relay operates when the average value of the operate input exceeds the average value of the restrain input by an amount greater than the setting.

a. Circuit

The comparator design on which this model is based consists of two full-wave rectifiers, one for each input, the outputs of which are connected so that the restrain input will oppose the operate input. This difference output is offset by a setting-dependent bias and integrated between two output limits. The comparator thus operates on the difference between the average operate and restrain quantities.

b. Equations as programmed

The output is computed from trapezoidal integration of

$$|i_{op}(t)| - |i_{rest}(t)| - \text{bias}$$

where

i_{op} is the operate current

i_{rest} is the restrain current

bias is the setting control current.

Hence

$$\text{output}(k) = \text{output}(k-1) + \text{gain}\ \frac{\Delta t}{2} \cdot$$
$$(|i_{op}(k)|-|i_{rest}(k)|+|i_{op}(k-1)|-|i_{rest}(k-1)|-2\cdot\text{bias})$$

where gain is the integrator gain, and Δt is the time step.

The value gain is computed in generally the same manner as was described for the maximum gain for the inverse-time overcurrent model. The gain is computed to ensure that the maximum measurement ripple for an input just below setting will not quite cause comparator operation. For this dual-input comparator, the peak ripple is dependent on the maximum possible value of the restraining input under no-fault conditions. The details of the gain calculation are too involved to be included here.

The value of `output` is constrained to lie within two range limits.

c. *Initialization*

Initial values are required for the input signals and the integrator output voltage. The input signals are described by:

$$i_{op}(t) = \hat{I}_{op} \cos(\omega_s t + \theta_{op})$$

$$i_{rest}(t) = \hat{I}_{rest} \cos(\omega_s t + \theta_{rest})$$

where the values of $\hat{I}_{op}$, $\hat{I}_{rest}$, θ_{op}, and θ_{rest} are obtained as described in section 2.

Initialization of the integrator output is by "silent simulation", rather than by direct computation as with the other comparators. With silent simulation, a simulation is performed for which intermediate values of the simulation variables are discarded, and only the final values are retained (see chapter IV). Although a brute force technique, it is an effective (although not necessarily the least expensive) method of initializing highly nonlinear networks. The technique is reliable here as long as the comparator output reaches one of the output limits during the one cycle which is used for initialization.

11. Permissive-Trip Model

The permissive-trip model contains both the permissive trip logic (figs. 11 and 12) and the repeat-if-no-block (RINB) logic (fig. 13). It is clear from fig. 11 that the model involves a feedback loop for $\mathbf{PTTX_B}$ (which is delayed by the channel propagation time before being fed back). Because of the feedback, the permissive-trip model uses the simultaneous approach (i.e. simulate the entire subsystem for each time step) internally, even though the simulation as a whole uses the sequential simulation approach (i.e. simulate the complete response of one model before proceeding to another).† The permissive-trip model is an example of how logic feedback can be handled in the sequential approach.

The simultaneous approach requires single-step models of the permissive-trip and RINB logic to be used. The logic of the permissive-trip sub-block (fig. 12) is straight-forward. The RINB sub-block (fig. 13) is more complex, since the timer model‡ includes its own feedback loop within the internal SR flipflop. The two levels of feedback cause no special difficulty, however, since, except for some temporary storage, each sub-block is self-contained.

12. Positive-Sequence Filter Modelling

The filter modelled here is that used in the Westinghouse S1G-1H positive-sequence-restrained overcurrent relay. This filter is shown in the Westinghouse T&D Book (Westinghouse, 1964, fig. 31h, pg. 374). It has the advantage for this application of providing both positive-sequence and residual current outputs.

†See chapter IV for a discussion of these two approaches.
‡The timer model is a single-step version of the timer model described in section 18.

a. Circuit

Figure 31(a) shows the circuit for the positive-sequence filter, while fig. 31(b) shows the equivalent circuit (the transactor having been replaced by its magnetizing inductance and a current source).

b. Derivation of the state equations

The differential equation describing the circuit is (writing the equation for the principal loop)

$$v_o + L_m(\dot{i}_c - \dot{i}_b + \frac{1}{R_1}\dot{v}_o) + \tfrac{2}{3}R(\frac{v_o}{R_1} - i_a) + \tfrac{1}{3}R(\frac{v_o}{R_1} + i_b + i_c) = 0$$

where i_a, i_b, and i_c are the phase currents, and the remaining variables are as noted in fig. 31.

Collecting terms in v_o

$$\frac{L_m}{R_1}\dot{v}_o + v_o(1 + \frac{R}{R_1}) = L_m(\dot{i}_b - \dot{i}_c) + R(i_a - i_0).$$

where

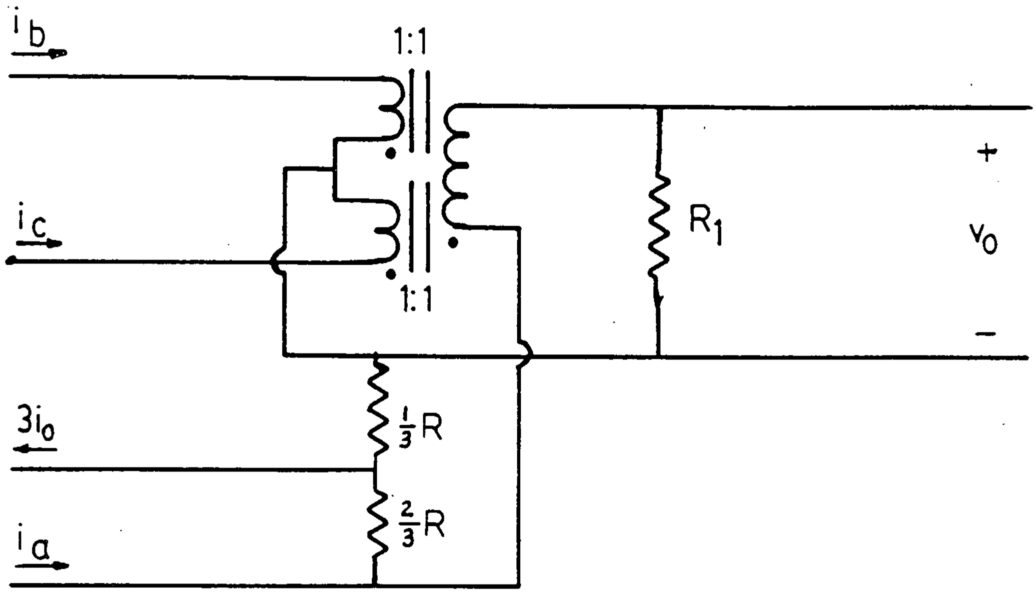
$$L_m = \frac{R}{\sqrt{3}\omega_s}$$

$$i_0 = \tfrac{1}{3}(i_a + i_b + i_c)$$

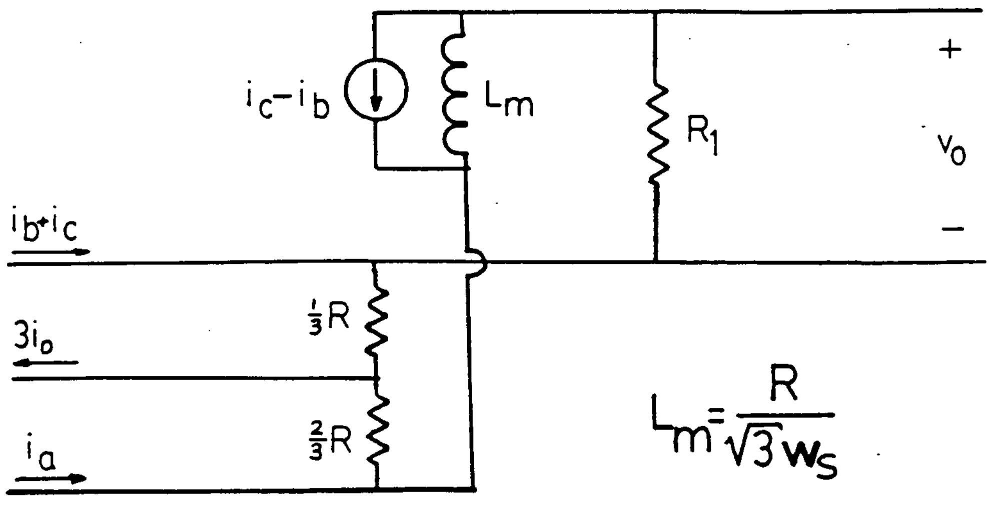
The gain of the filter is to be one, which places a constraint on the values of R and R_1.

As a phasor expression the differential equation is

$$j\frac{R}{\sqrt{3}R_1}V_o + V_o(1 + \frac{R}{R_1}) = j\frac{R}{\sqrt{3}}(I_b - I_c) + R(I_a - I_0).$$



(a) Circuit arrangement



(b) Equivalent circuit

Fig. 31. Positive-sequence filter equivalent circuit.

Solving for V_o

$$V_o = \frac{RR_1}{R_1+R+j\frac{R}{\sqrt{3}}} \cdot 2I_1.$$

The gain is thus

$$\frac{2RR_1}{(R_1^2+2RR_1+\frac{4}{3}R^2)^{1/2}}.$$

For the gain to be unity,

$$(2RR_1)^2 = R_1^2 + 2RR_1 + \tfrac{4}{3}R^2$$

which can be solved for R_1 to get

$$R_1 = \frac{R}{(4R^2-1)}\{1+(\frac{16}{3}R^2-\frac{1}{3})^{1/2}\}$$

which is real and positive for $R > 1/2$.

In standard form (section 4) the differential equation is

$$D\dot{y} = Ay + Bu + C\dot{u}$$

where

$$y = v_o$$

$$u = \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_0 \end{bmatrix}$$

$$A = -(1 + \frac{R}{R_1})$$

$$B = \begin{bmatrix} R & 0 & 0 & -R \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & L_m & -L_m & 0 \end{bmatrix}$$

$$D = \frac{L_m}{R_1}$$

c. *Equations as programmed*

The differential equation derived earlier is programmed using central differences, as described in section 4. The transition equation is, in standard form,

$$y^k = Ey^{k-1} + Fu^k - Gu^{k-1}$$

where the matricies E, F, and G are

$$E = \frac{\frac{2L_m}{\Delta t} - R_1 - R}{\frac{2L_m}{\Delta t} + R_1 + R}$$

$$F = \begin{bmatrix} R & \frac{2L_m}{\Delta t} & -\frac{2L_m}{\Delta t} & -R \end{bmatrix} \cdot \frac{R_1}{\frac{2L_m}{\Delta t} + R_1 + R}$$

$$G = \begin{bmatrix} -R & \frac{2L_m}{\Delta t} & -\frac{2L_m}{\Delta t} & R \end{bmatrix} \cdot \frac{R_1}{\frac{2L_m}{\Delta t} + R_1 + R}$$

d. Initialization

Initial conditions are required for the phase currents i_a, i_b, and i_c, the residual current $3i_0$, and the positive-sequence output voltage v_o.

The phase currents can be found from

$$i_a(t) = \hat{I}_a \cos(\omega_s t+\theta_a),$$

$$i_b(t) = \hat{I}_b \cos(\omega_s t+\theta_b), \text{ and}$$

$$i_c(t) = \hat{I}_c \cos(\omega_s t+\theta_c),$$

where $\hat{I}_a$, $\hat{I}_b$, $\hat{I}_c$, θ_a, θ_b, and θ_c are found as described in section 2.

The residual current is just the sum of the three phase currents. The output voltage may be found by writing the phasor expression found earlier for V_o in terms of I_A, I_B, and I_C only, to get

$$V_o = \frac{2}{3} \cdot \frac{RR_1}{R_1+R+j\frac{R}{\sqrt{3}}} (I_a+e^{j120°}I_b+e^{-j120°}I_c)$$

so that

$$v_o(t) = \tfrac{1}{3}(\hat{I}_a\cos(\omega_s t+\theta_a+\theta) + \hat{I}_b\cos(\omega_s t+\theta_b+120°+\theta) + \hat{I}_c\cos(\omega_s t+\theta_c-120°+\theta))$$

where

$$\theta = -\arctan(\frac{R}{\sqrt{3}(R_1+R)}.)$$

13. Westinghouse SD-2H Modelling

The phase-fault distance relays are Westinghouse Canada type SD-2H units, which are block-instantaneous memory-polarized mho relays. The ZI-V input is tuned to reduce susceptibility to high-frequency voltage-derived transients and low-frequency transients associated with series capacitors. The Q of the circuit is kept low under normal conditions to prevent the memory action of the tuned circuit from excessively delaying relay operation. The delay is most severe for faults barely within the relay reach. Under fault-conditions the ZI-V circuit is switched to a high-Q configuration by fault-detecting relay 21LX (Westinghouse Canada type SDX-1H).

Relay 21LX also inserts a pickup delay of 35-45 ms into the output of the SD-2H units for 21L1 and 21L2 (provided they have not already operated). The purpose of the delay is to prevent relay misoperation due to transients associated with fault clearing or switching of the input filter.

A "load angle compensator" (Westinghouse Canada LAC-1H) is used to modify the voltages applied to 21L3. The modified voltages ensure coordination under transient conditions between reverse blocking relay 21L3 at one terminal and the overreaching relay 21L2 at the opposite terminal (see chapter 2). A complete description of the SD-2H and SDX-1H relays is given in the manufacturer's instruction manual I.L. H41-1302E (Westinghouse Canada, 1979).

The phase comparator used in this model is not block-instantaneous; it is the block-average phase comparator described in section 7. The transient behaviour of the model can be expected to be somewhat different than that of the actual relay.

a. SD-2H input circuits

A somewhat simplified schematic of the SD-2H input circuits is shown in fig. 32(a). The polarizing voltage is obtained from a series RLC memory circuit, and so can be modelled using the general memory/filter model of section 8.

The input circuit for the IZ-V voltage is essentially a double-tuned circuit with a switchable Q, as can be seen from the simplified equivalent circuit of fig. 32(b). The Q of the circuit can be increased by closing the contact across resistor R_2 in the series resonant circuit.

The reach and line angle of the relay are set by the parallel combination of L_3 (transactor magnetizing inductance) and R_3, which together form impedance Z_3. If the parallel combination of the current source (transactor) and Z_3 is replaced by an equivalent Thevenin network (at $\omega = \omega_S$), it is clear that the net forcing voltage is $I Z_3$-V, so that the replica impedance $Z_C = Z_3$.

For proper operation of the relay, it is essential that the output voltage be in phase with the input voltage regardless of the position of the contacts. The transfer function at $\omega = \omega_S$ can be shown to be

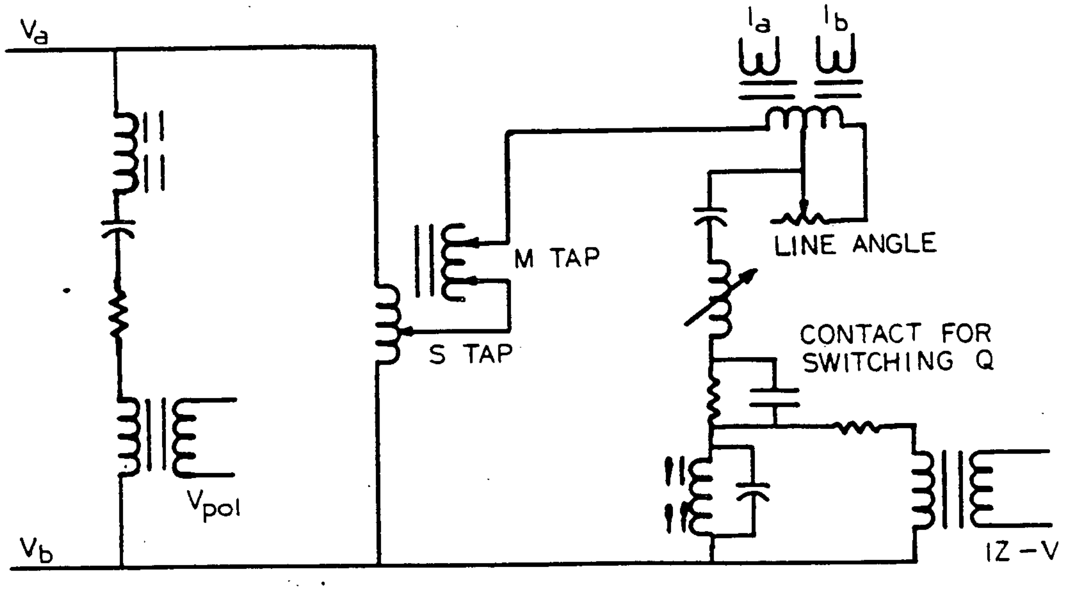
$$\frac{jR_1X_p}{(R_sR_1 - X_sX_p) + j(R_1X_p + X_sR_1 + X_pR_s)}$$

where

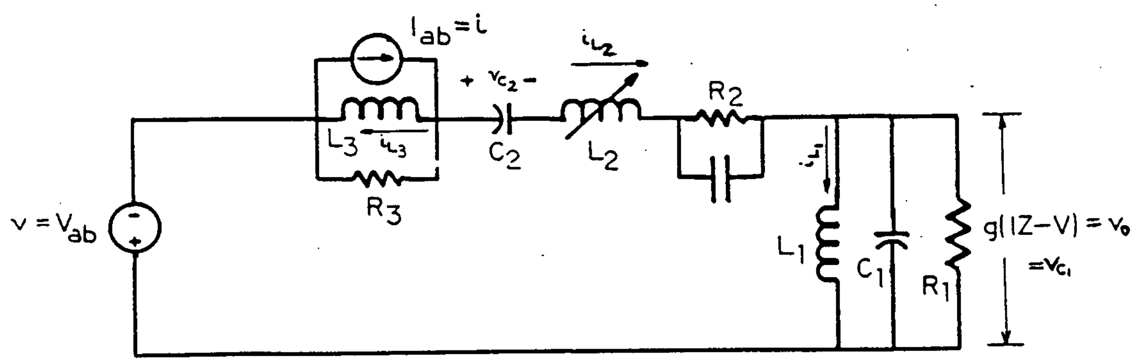
$$R_s = R_2 + |Z_C|\cos\theta_{Z_C}$$

$$X_s = X_{L_2} - X_{C_2} + |Z_C|\sin\theta_{Z_C}$$

$$X_p = X_{L_1}/(1 - X_{L_1}Y_{C_1})$$



(a) slightly simplified circuit diagram



(b) equivalent circuit for IZ-V input

Fig. 32. SD-2H input circuits.

This transfer function must be real for V_o and V to be in phase. One condition which yields a real transfer function is

$$R_sR_1 - X_sX_p = 0,$$

which, however, cannot hold for the two values of R_s corresponding to the two contact positions. The only other possible solution is if X_p tends to infinity and $X_s = 0$, so that

$$V_o = \frac{R_1}{(R_1+R_s)} V$$

Thus L_1 and C_1 must be resonant at $\omega = \omega_s$,

$$L_1C_1 = \omega_s^{-2}$$

as must L_c+L_2 and C_2

$$(L_c+L_2)C_2 = \omega_s^{-2}$$

where

$$\omega_s L_c = |Z_c| \sin \theta_{Z_c}$$

It is now possible to find L_1, C_1, R_3, and L_3 given C_1, L_2, $|Z_C|$, and θ_{Z_C}. The latter two values are settings, and so are known. It remains to find values for R_1, R_2, C_1, and L_2.

The quality factor (Q) at resonance may be used to specify the degree of filter "sharpness" required. The Q at resonance may be determined from the ratio of the total energy stored to the average power loss. The energy stored is the sum of the energies in L_3, L_2, C_2, L_1, and C_1. The energy stored in

L_1 and C_1 is constant and equal to

$$\tfrac{1}{2}C_1\ \hat{V}^2_{C_1}$$

where $\hat{V}_{C_1}$ is the peak value of the voltage across C_1, which at resonance ($\omega=\omega_0$) is $R_1\hat{I}_{L_2}$, so that the energy stored in C_1 and L_1 is

$$\tfrac{1}{2}C_1(R_1\hat{I}_{L_2})^2$$

where $\hat{I}_{L_2}$ is the peak value of the current through L_2.

The energy in C_2 is zero, and the energy in L_2 is a maximum, at the peak of i_{L_2}. The energy stored in C_2 and L_2 at the instant of $\hat{I}_{L_2}$ is thus

$$\tfrac{1}{2}L_2\hat{I}^2_{L_2}$$

The energy stored in L_3 at this same instant is

$$\tfrac{1}{2}L_3 i^2_{L_3}$$

where

$$i_{L_3} = \left|\frac{R_3}{R_3+j\omega_0 L_3}\right| \cos(-\arctan\frac{\omega_0 L_3}{R_3})\cdot\hat{I}_{L_2}$$

Thus the total stored energy (which is constant) is

$$\tfrac{1}{2}\{C_1R_1^2+L_2+L_3\left|\frac{R_3}{R_3+j\omega_0 L_3}\right|^2 \cos^2(-\arctan\frac{\omega_0 L_3}{R_3})\}\cdot\hat{I}_{L_2}$$

The average power dissipation at resonance is equal to the sum of the powers dissipated in R_1, R_2, and R_3. The average power dissipated in R_1 and R_2 is

$$\tfrac{1}{2}(R_1+R_2)\hat{I}^2_{L_2}$$

The average power dissipated in R_3 is

$$\tfrac{1}{2}R_3\hat{I}^2_{R_3}$$

where

$$\hat{I}_{R_3} = \left|\frac{j\omega_0 L_3}{R_3+j\omega_0 L_3}\right| \cdot \hat{I}_{L_2}$$

The total power dissipated is thus

$$\tfrac{1}{2}\left(R_1+R_2+R_3\left|\frac{\omega_0 L_3}{R_3+j\omega_0 L_3}\right|^2\right) \cdot \hat{I}^2_{L_2}$$

The circuit Q (under steady-state conditions at $\omega=\omega_0$) is thus

$$Q = \omega_0 \frac{C_1R_1^2+L_2+L_3'}{R_1+R_2+R_3'}$$

where

$$R_3' = R_3\left|\frac{\omega_0 L_3}{R_3+j\omega_0 L_3}\right|^2$$

$$L_3' = L_3\left|\frac{R_3}{R_3+j\omega_0 L_3}\right|^2 \cos^2\left(\arctan\frac{\omega_0 L_3}{R_3}\right)$$

With the contacts closed, the Q is high and equal to

$$Q_H = \omega_0 \frac{C_1R_1^2+L_2+L_3'}{R_1+R_3'}$$

R_1 is selected to ensure that $C_1R_1{}^2 + L_2 > 0$. Rearranging the above expression for Q_H

$$C_1R_1^2 + L_2 = (R_1+R_3')\frac{Q_H}{\omega_o} - L_3'$$

so that

$$R_1 > \frac{L_3'\omega_o}{Q_H} - R_3'.$$

Now set $L_2 = C_1R_1{}^2$, thus ensuring that both L_2 and C_1 are positive, with

$$L_2 = \tfrac{1}{2}\{(R_1+R_3')\frac{Q_H}{\omega_o} - L_3'\}, \text{ and}$$
$$C_1 = \frac{L_2}{R_1^2}$$

The value of R_2 can be found from the ratio of high and low values of Q:

$$\frac{Q_H}{Q_L} = \frac{R_1+R_2+R_3'}{R_1+R_3'}$$

Solving for R_2:

$$R_2 = (R_1+R_3')(\frac{Q_H}{Q_L} - 1)$$

All circuit values are now known.

b. Derivation of the state equations

The state and input variables are

$$y = \begin{bmatrix} i_{L_1} \\ i_{L_2} \\ i_{L_3} \\ v_{C_1}=v_o \\ v_{C_2} \end{bmatrix}$$

$$u = \begin{bmatrix} i \\ v \end{bmatrix}$$

where the variables are as shown in fig. 32.

The state equations are

$$\dot{i}_{L_3} = \frac{R_3}{L_3}(i-i_{L_2}-i_{L_3})$$

$$L_3\dot{i}_{L_3} - L_2\dot{i}_{L_2} = v + v_{C_2} + R_2 i_{L_2} + v_o$$

$$C_2\dot{v}_{C_2} = i_{L_2}$$

$$C_1\dot{v}_o = i_{L_2} - \frac{v_o}{R_1} - i_{L_1}$$

$$L_1\dot{i}_{L_1} = v_o$$

Arranging in the standard form (section 4)

$$D\dot{y} = Ay + Bu$$

and noting that

$$\frac{R_3}{L_3} = \omega_s Q_3$$

the matricies A, B, and D are

$$D = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & -L_2 & L_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & C_2 \\ 0 & 0 & 0 & C_1 & 0 \\ L_1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$A = \begin{bmatrix} 0 & -\omega_s Q_3 & -\omega_s Q_3 & 0 & 0 \\ 0 & R_2 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 \\ -1 & 1 & 0 & -R_1^{-1} & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} \omega_s Q_3 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

c. *Equations as programmed*

The differential equations are programmed using central differences, as described in section 4. The transition equation is, in standard form,

$$y^k = Ey^{k-1} + Fu^k - Gu^{k-1}$$

where the matricies E, F, and G are

$$E = \left(\frac{2}{\Delta t} D - A\right)^{-1}\left(\frac{2}{\Delta t} D + A\right)$$

$$F = \left(\frac{2}{\Delta t} D - A\right)^{-1} B$$

$$G = -F$$

The above equation is solved using the University of B. C. Computing Centre routine SLIMP (Nicol, 1982), which uses Gaussian elimination with an iterative improvement algorithm.† To use SLIMP, it is necessary (for efficiency) to rearrange the standard form equation into

$$Hy^k = HEy^{k-1} + HFu^k - HGu^{k-1}$$

where $H = \left(\frac{2}{\Delta t} D - A\right)$.

The right-hand side of the equation is compiled at each time step, and SLIMP is used to find the solution to

$$Hy^k = x^k$$

where x^k is the right-hand side at step k.

†This improvement may not have been required—it was used because it was available and provided some protection in the event the matrix was ill-conditioned, at little increase in overall computation time.

d. Initialization

Initial values are required for the input voltage and current, and for all state variables. The expressions for the input voltage and current are

$$v(t_0) = \hat{V}\cos(\omega_s t_0+\theta_V)$$

$$i(t_0) = \hat{I}\cos(\omega_s t_0+\theta_I)$$

where $\hat{V}$, $\hat{I}$, θ_V, and θ_I are obtained as described in section 2.

The analysis for the state variable initial conditions is simplified by using a Thevenin equivalent source network. The current source and parallel combination of R_3 and L_3 can be converted to a Thevenin equivalent with open-circuit voltage $E = Z_C I$, where I is the phasor input current, and impedance

$$Z_C = \frac{\omega_s^2 L_3^2 R_3 + j\omega_s L_3 R_3^2}{R_3^2+\omega_s^2 L_3^2} = R_C + j\omega_s L_C$$

Now let

$$Z_1 = \frac{1}{\dfrac{1}{R_1} + \dfrac{1}{j\omega_s L_1} + j\omega_s C_1}$$

and

$$Z_{tot} = Z_1+R_2+Z_C+j\omega_s L_2 + \frac{1}{j\omega_s C_2}$$

The total driving voltage is now $IZ_C - V$ and the output voltage, by voltage divider action, is

$$V_o = \frac{Z_1}{Z_{tot}}(IZ_C - V)$$

The phasor expressions for the other state variables are:

$$I_{L_1} = \frac{V_o}{j\omega_s L_1} = \frac{Z_1}{j\omega_s L_1 Z_{tot}}(IZ_C - V)$$

$$I_{L_2} = \frac{(IZ_C-V)}{Z_{tot}}$$

$$V_{C_2} = \frac{I_{L_2}}{j\omega_s C_2} = \frac{1}{j\omega_s C_2 Z_{tot}}(IZ_C-V)$$

and finally, since the voltage across L_3 is $(I-I_{L_2})Z_C$,

$$I_{L_3} = \frac{V_{L_3}}{j\omega_s L_3} = \frac{Z_C}{j\omega_s L_3 Z_{tot}}\{(Z_1+Z_2)I+V\}$$

where

$$Z_2 = R_2+j\omega_s L_2+\frac{1}{j\omega_s C_2}$$

The values $y(t_0)$ are found by using the derived phasor expressions for Y_i to get

$$y_i(t_0) = \sqrt{2}|Y_i| \cos(\omega_s t_0+\theta_i)$$

where $\theta_i = \arg(Y_i)$.

e. SD-2H output stage

The output stage of the SD-2H includes the circuitry for the insertion of a pickup delay, as controlled by the SDX-1H fault-detecting relay. The delay is inserted only if the SD-2H output is not already high at the time the insert-delay control input goes high.

The circuitry which is used in the model to provide the delay insertion feature is shown in fig. 33. The control logic, consisting of two inverters and an AND gate, enables or disables the AND gate which bypasses the delay

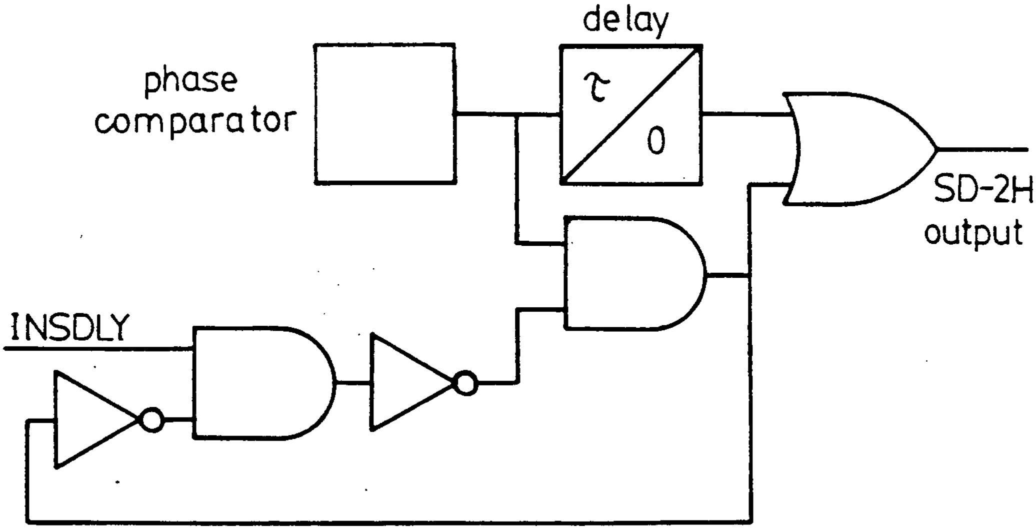


Fig. 33. SD-2H output circuit (as modelled)

timer†, according to the state of the insert-delay control input. The feedback in the control circuit disables the control input in the event the SD-2H unit has already picked up.

The logic feedback loop in the control circuit leads in the program to a FORTRAN DO loop enclosing the control logic. The reason for the loop is that initially the value being fed back (the output) is unknown, and so must be assumed. A first iteration will propagate the effect of the assumption through the model. At the end of the first iteration the output (feedback) value will correspond to the assumed input (feedback) value. If the output value is the same as was initially assumed, no further iterations are required. If the output value is different than was initially assumed, one final iteration will be required. If the simulated logic is stable, the final iteration must produce no change in

†The timer element is the same as for the timer model described in section 18.

the output feedback signal.

All logic is performed using NLR.

14. Modelling for Westinghouse SDX-1H Fault-detecting Relay

The fault-detecting relay 21LX is a Westinghouse Canada type SDX-1H unit, which is a combination negative sequence/undervoltage relay. Timer units are used in the output stage to control the switching of the input filters for 21L1, 21L2, and 21L3, and the pickup delays for 21L1 and 21L2.

A simplified diagram of this unit is shown in fig. 34. In the actual device, the undervoltage unit is a three-phase device; three single phase elements are used in the model for simplicity. (The difference did not appear to cause any adverse effects.) The purpose of the undervoltage unit is to ensure continued operation of the SDX-1H relay for three-phase faults.

The negative sequence device consists of a negative sequence filter and an overvoltage element. This is the principal fault-detecting element, and operates at fault inception for all fault types.

The filter-switching output stage consists of an SR flipflop which is set upon operation of either the negative sequence or undervoltage device. The flipflop receives a reset pulse every 90-120 ms (modelled as 100 ms) from a unijunction relaxation oscillator. The filter switching (***SWQ***) output is driven from the normal ("Q") output of the flipflop.

The same output drives the SET input of a second SR flipflop through a 30-40 ms (modelled as 35 ms) delayed-pickup timer. Thus 35 ms after the ***SWQ*** output goes high, the second flipflop receives a SET impulse, turning on the ***INSDLY*** insert delay output to cause the insertion of a pickup delay in

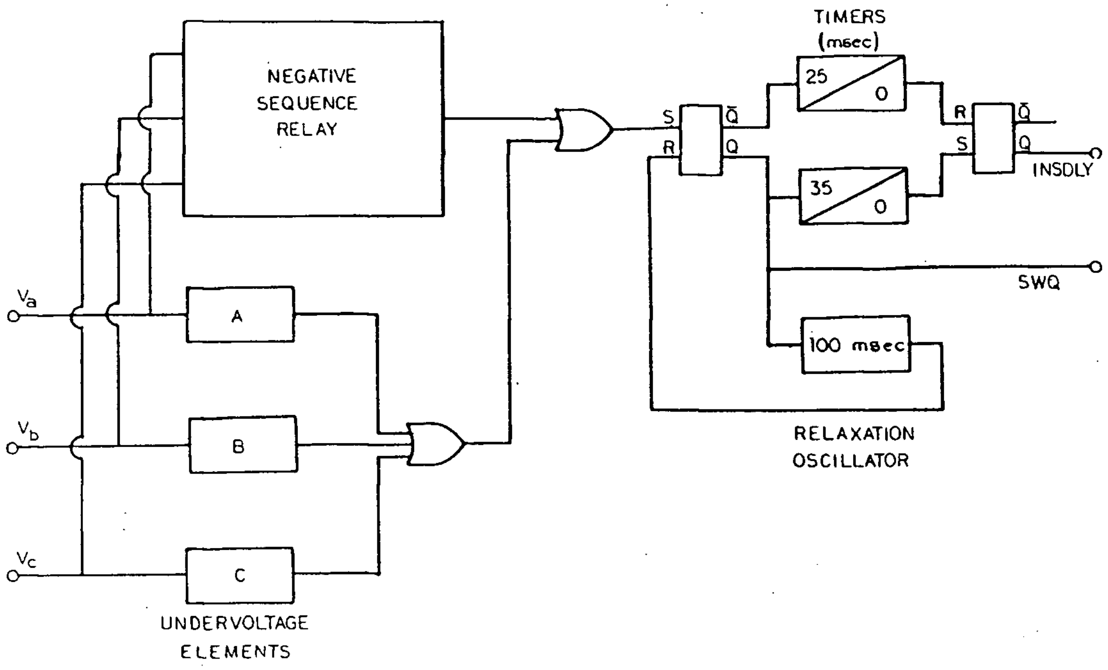


Fig. 34. SDX-1H general layout

21L1 and 21L2. The second flipflop is reset 20-60 ms (modelled as 25 ms) after reset of the first flipflop. The reset input of the second flipflop is driven through a delayed-pickup timer from the inverted ("$\bar{Q}$") output of the first flipflop.

A complete description of this relay is given in the manufacturer's instruction manual I.L. H41-1302E (Westinghouse Canada, 1979).

The SR flipflop and delayed pickup timer models are described in section 18 for the delayed-pickup/delayed-dropout timer model. The relaxation oscillator provides feedback around the first flipflop, so that the two models must be treated using the simultaneous approach within a FORTRAN DO loop. The composite model forms a timed-reset latch. The SR flipflop portion of the latch is a single-step version of the flipflop described in section 18.

The relaxation oscillator is based on a standard unijunction relaxation oscillator. The oscillator can be turned on and off with an input signal. The model produces a high output for one time step at the first step after the oscillation period has elapsed, and repeats at equal intervals thereafter. When the oscillator is turned off, the output is equal to the input switching waveform. (This is for increased usefulness of the model with NLR.)

An input of exactly zero is taken as a positive input if the oscillator is already on, or a negative input if the oscillator is off. The timing state of the oscillator is reset when the oscillator is turned off.

15. Undervoltage Relay

The undervoltage relay model is implemented using the inverse-time overcurrent model as a single-input amplitude comparator. The overcurrent model is set for "instantaneous" operation by setting TMS = 1. The voltage being monitored is applied directly as the input to the "overcurrent" model, the output of which is negated (NLR inversion) to produce a "b" contact output.

16. Negative-sequence Relay

The negative-sequence relay model is implemented using the inverse-time overcurrent relay model as a single-input amplitude comparator. The overcurrent model is set for "instantaneous" operation by setting TMS = 1. The output from a negative sequence filter is applied directly as the input of the "overcurrent" model.

a. Circuit

The circuit used for the negative-sequence filter is shown in fig. 35. This circuit is essentially a memory circuit driven by v_{AB}, the output of which is v_{1B}. The output of the filter is

$$v_{1m} = v_{1B} - v_{mB}$$

$$= v_{1B} - \tfrac{1}{2}v_{CB}$$

b. Derivation of equations

The filter is implemented using the memory model, the output of which is scaled and combined with $\frac{1}{2}v_{CB}$.

The steady-state output of the filter can be found from the phasor equations. By voltage-divider action,

$$V_{1B} = \frac{R}{R+j(\omega_s L - \frac{1}{\omega_s C})} V_{AB}$$

Since $|X_C|-|X_L| = \sqrt{3}R$,

$$\frac{1}{\omega_s C} - \omega_s L = \sqrt{3}R$$

and

$$V_{1B} = \frac{1+j\sqrt{3}}{4} v_{AB} = -\frac{a^2}{2} v_{AB}$$

where $a = e^{j120°}$

The v_{1m} output voltage is thus

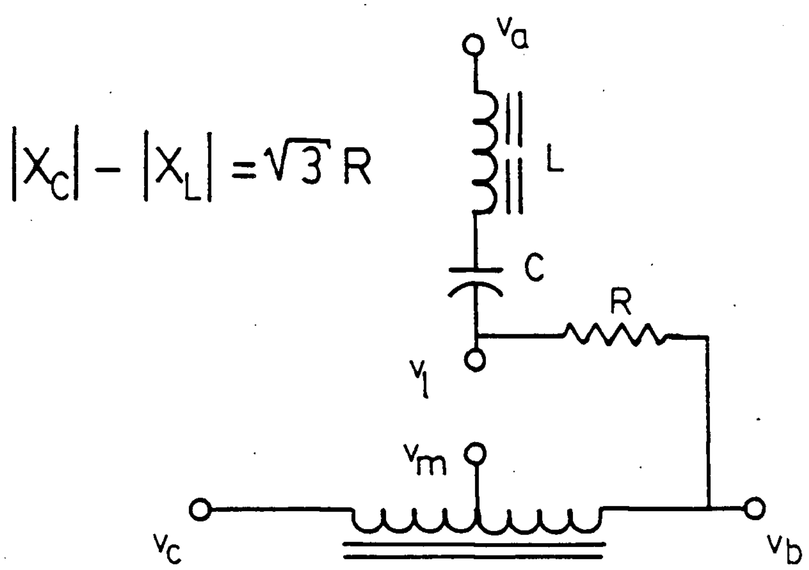


Fig. 35. Negative-sequence filter equivalent circuit

$$-\tfrac{1}{2}a^2(V_A+a^2V_B+aV_C) = -\tfrac{3}{2}a^2V_2$$

The voltage v_{1m} is internally scaled by a factor of $\frac{2}{3}$ to obtain the filter output, which is thus

$$-a^2V_2$$

c. *Equations as programmed*

The memory circuit must be operated off resonance to obtain the correct relationship between X_C and X_L. Both the resonance frequency and the Q of the memory are required. The Q is specified as a parameter.

To find an expression for the resonance frequency ω_0, start with the equations for memory Q

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 CR}.$$

where $\omega_0 = (LC)^{-1/2}$

Substituting this expression into the relation between X_C and X_L gives

$$Q(\frac{\omega_0}{\omega_S} - \frac{\omega_S}{\omega_0}) = \sqrt{3}$$

which rearranges to

$$\omega_0^2 - \frac{\sqrt{3}\omega_0\omega_S}{Q} - \omega_S^2 = 0$$

which can be solved to get

$$\omega_0 = \{\frac{\sqrt{3}}{2Q} + \tfrac{1}{2}(\frac{3}{Q^2}+4)^{-1/2}\}\omega_S$$

17. Load Angle Compensator Modelling

a. Circuit

The Load Angle Compensator (LAC) is essentially a series-tuned transactor, as can be seen from the equivalent circuit in fig. 36 (where the transactor has been replaced by a current source and its magnetizing inductance). The output is the voltage across the load resistance.

The circuit Q, the gain g, and the resonance frequency ω_0 are all specified as parameters. The values of the circuit constants R, L, and C are computed from the specified parameters as follows.

The circuit Q at $\omega = \omega_0$ is given by

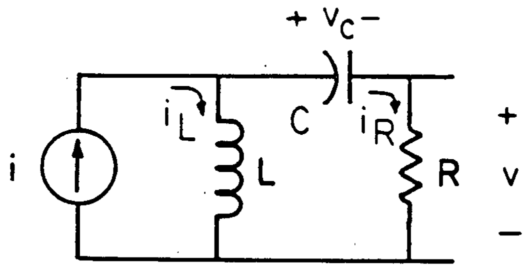


Fig. 36. Load angle compensator equivalent circuit

$$Q = \frac{1}{\omega_0 CR} = \frac{\omega_0 L}{R}$$

where $\omega_0 = (LC)^{-1/2}$. The gain of the circuit at $\omega=\omega_0$ can be found by replacing the current source and magnetizing inductance with a Thevenin equivalent at $\omega=\omega_0$. The open-circuit voltage at $\omega=\omega_0$ is then equal to V, so that

$$V = j\omega_0 LI.$$

The gain is thus

$$g = \frac{|V|}{|I|} = \omega_0 L$$

Solving for L

$$L = g/\omega_0.$$

Substituting for L in the inductive expression for Q and solving for R gives

$$R = g/Q.$$

Substituting for R in the capacitive expression for Q and solving for C gives

$$C = (\omega_0 g)^{-1}$$

b. Derivation of state equations

The differential equations describing the LAC are

$$C\dot{v}_C = i - i_L$$

$$L\dot{i}_L = (i - i_L)R + v_C$$

where the variables are identified in fig. 36.

In standard form (section 4)

$$D\dot{y} = Ay + Bu + C\dot{u}$$

where

$$y = \begin{bmatrix} v_C \\ i_L \end{bmatrix}$$

$$u = i$$

$$D = \begin{bmatrix} C & 0 \\ 0 & L \end{bmatrix}$$

$$A = \begin{bmatrix} 0 & -1 \\ 1 & -R \end{bmatrix}$$

$$B = \begin{bmatrix} 1 \\ R \end{bmatrix}$$

$$C = \bar{0}$$

The output is

$$v = (i - i_L)R$$

$$= (u - y_2)R$$

c. Equations as programmed

The differential equations are programmed using central differences, as described in section 4. The transition equation is, in standard form,

$$y^k = Ey^{k-1} + Fu^k - Gu^{k-1}$$

where

$$E = \frac{1}{det}\begin{bmatrix} \frac{4LC}{\Delta t^2}+\frac{2RC}{\Delta t}-1 & -\frac{4L}{\Delta t} \\ \frac{4C}{\Delta t} & -1-\frac{2RC}{\Delta t}+\frac{4LC}{\Delta t^2} \end{bmatrix}$$

$$B = \frac{1}{det}\begin{bmatrix} \frac{2L}{\Delta t} \\ 1+\frac{2RC}{\Delta t} \end{bmatrix}$$

$$G = -F$$

where $det = \dfrac{4LC}{\Delta t^2} + \dfrac{2RC}{\Delta t} + 1$

The output is

$$v^k = (u^k - y_2^k)R$$

d. Initialization

Initial values are required for the input current and the state variables v_C and i_L. The input current is given by

$$i(t_0) = \hat{I}\cos(\omega_s t_0+\theta)$$

where t_0 is the initial time, and $\hat{I}$ and θ are found as described in section 2.

The phasor equations for the state variables may be found from the state equations

$$j\omega_s C V_C = I - I_L$$

$$j\omega_s L I_L = (I-I_L)R + V_C$$

Substituting the first equation for V_C in the second equation and solving for I_L gives

$$I_L = \frac{1+j\omega_s RC}{1-\omega_s^2 LC+j\omega_s RC} I$$

Substituting now for I_L in the first equation and solving for V_C gives

$$V_C = \frac{j\omega_s L}{1-\omega_s^2 LC+j\omega_s RC} I$$

Thus the initial magnetizing current is

$$i_L(t_0) = \hat{I}_L \cos(\omega_s t_0+\theta+\theta_L)$$

where

$$\hat{I}_L = \frac{|1+j\omega_s RC|}{|1-\omega_s^2 LC+j\omega_s RC|}\,\hat{I}$$

$$\theta_L = \arctan(\omega_s RC) - \arctan\left(\frac{\omega_s RC}{1-\omega_s^2 LC}\right)$$

and the initial capacitor voltage is

$$v_C(t_0) = \hat{V}_C \cos(\omega_s t_0+\theta+\theta_C)$$

where

$$\hat{V}_C = \frac{|j\omega_s L|}{|1-\omega_s^2 LC+j\omega_s RC|}\,\hat{I}$$

$$\theta_C = 90^\circ - \arctan\left(\frac{\omega_s RC}{1-\omega_s^2 LC}\right)$$

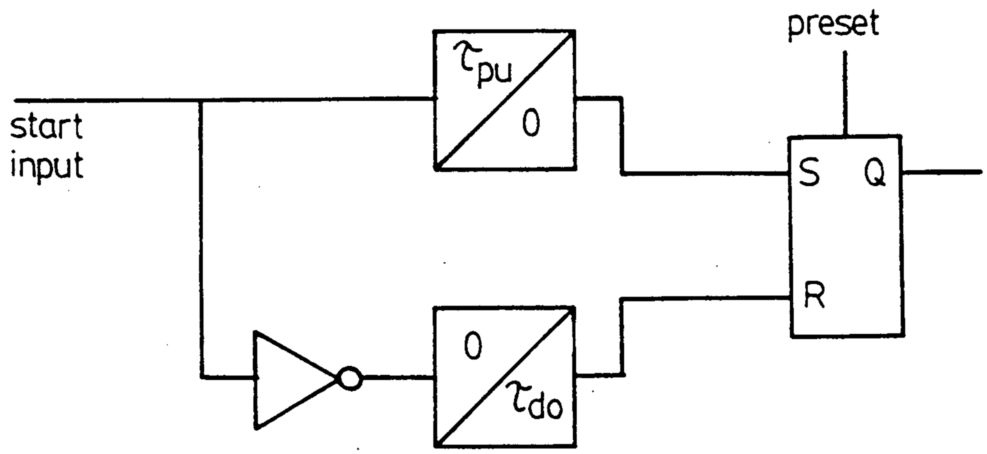
18. Delayed-pickup/delayed-dropout timer

a. Circuit

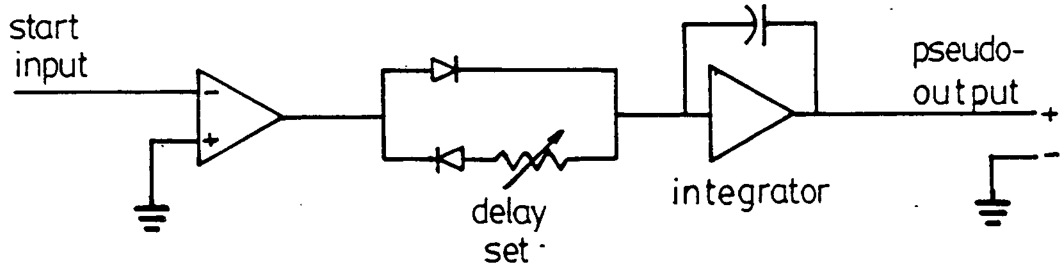
The delayed-pickup/delayed-dropout timer model consists of a delayed-pickup timer driving the SET input of a SR flipflop, and a delayed-dropout timer driving the RESET input, as shown in fig. 37(a). The timer output is taken from the normal ("Q") output of the flipflop.

b. Delayed-pickup and delayed-dropout timers

The delayed-pickup and delayed-dropout timers are almost identical, the only difference being the input polarity for which delayed operation occurs. A diagram of a circuit which is approximately equivalent to the delayed-pickup element is shown in fig. 37(b). The following description will apply to this



(a) Delayed pickup/delayed dropout timer unit



(b) Delayed pickup timer detail

Fig. 37. Delayed-pickup/delayed-dropout timer.

element, with the understanding that the delayed-dropout element is similar.

The delayed-pickup element begins timing when the input goes positive. Timing continues as long as the input remains positive, the output gradually becoming less negative over the timing interval. At the end of the time delay, the output is positive and is assigned a value equal to the input (as an enhancement for use with NLR).

When the input becomes negative the timer is immediately reset, the output being set to a fixed negative level. (The input must remain positive for the entire delay interval before the output will become high.)

The effect of a zero input value depends on the last non-zero input value. If that value was negative, the timer continues in a reset condition; if it was positive, the timer continues in a timing (or set) condition.

c. *SR flipflop*

The SR flipflop model is based on the classical cross-coupled NOR gate circuit, shown in the right-hand portion of fig. 38. The input section includes logic to force the S input to be dominant, thereby overcoming the indeterminacy which is characteristic of the basic SR flipflop when both inputs are high.

The feedback inherent in the flipflop requires the use of simultaneous modelling. All logic is implemented using NLR operations. The (single-step) logic is embedded within a FORTRAN DO loop, which iterates to a stable feedback condition (assuming one exists) within two iterations.

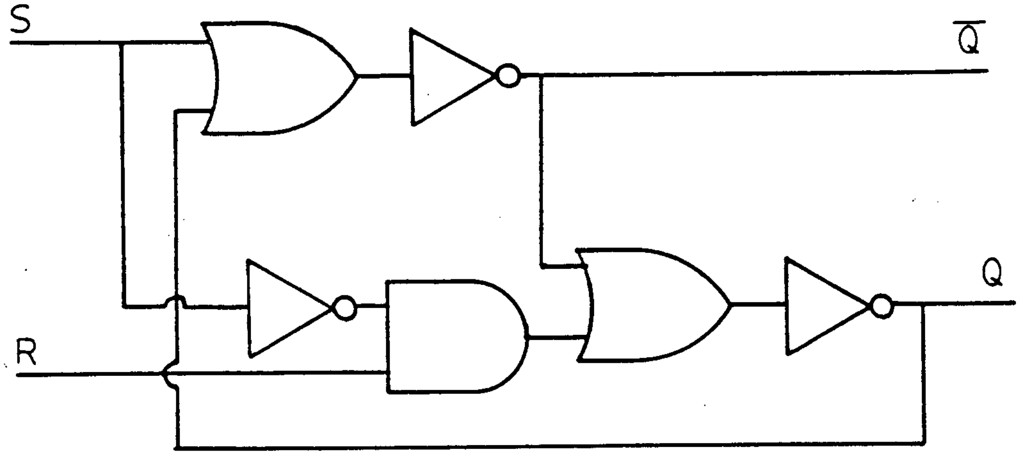


Fig. 38. SR flipflop logic, with S-input dominance

APPENDIX C

TRANSIENT RESPONSE PROCESSOR

A. INTRODUCTION

The Transient Response Processor (TRP) is a comprehensive package of software (written in ANS FORTRAN 77) for the manipulation and display of waveforms. Operation may be either interactive or "batch".

The TRP maintains an internal data area containing the waveforms, and has commands for adding data, deleting data, and saving the entire data area into external (mass-storage) files. A command is provided for plotting waveforms from the data area with minimum effort.

Input to the TRP and output from the TRP may be directed from/to any file or device (within operating system limitations).

Waveforms held by the TRP may be used as input to TRP-intrinsic or user-supplied functions, the output being added to the TRP data area as new waveforms. This feature permits the TRP to function as a special-purpose simulator.

B. SUMMARY OF OPERATION

When the TRP is started, the internal data area is empty. The **GET** command is used to read in data from external files. This data may then be **PLOT**ted, **DISPLAY**ed, or manipulated via the **COMPUTE** command. Data may be added to or deleted from the data area as required. The resulting data area may be **SAVE**d in TRP format at any point during TRP operation for use at a future time. Execution of the TRP is terminated with the **STOP** command.

C. STRUCTURE OF THE DATA

The data in the data area is organized into one or more **cases.** Each case has a distinct case title (which may be changed by the **SET** command). Each case has its own associated time base.

Within each case, the data is further organized into **entries.** Each entry has a **designator**, which must be unique within the associated case. Each entry is a vector of one or more **elements** (waveforms), and has a **data type** associated with it. The data type determines both the exact form of the designator and the default "units" (e.g. "Volts") used when plotting. The data type may also determine how the entry can be used in certain **functions** of the COMPUTE command.

The general form of a designator is

case:data-type:name(element)

where

case is a non-negative integer case number

data-type is an alphanumeric data type code

name is either a single or paired (i.e. **name1:name2**) character-string identifier

element is a non-negative integer identifying a specific waveform (**element**) of the **entry**.

Only the **data-type** and **name** must be specified (except where **data-type** is "TIME", indicating the time base, in which case neither **name** nor **element** may be specified). If **case** is not specified it defaults to case 1. If **element** is not specified, it defaults to element 0.

Case numbers are not necessarily preserved, and may change when data is saved or deleted. When data is added from an external file, the distinction between cases is preserved, but the case numbers become sequential to the cases already in the data area, starting at 1. (Case 0 is somewhat special—it need never exist, it must be explicitly created since it is never created from an external file, and it may be deleted without causing other cases to be renumbered.)

Valid **data types** are currently:

CV - Computed Value, generally arising from the use of the COMPUTE command

NV - Node Voltage, generally a phase-to-ground voltage within the power system

BV - Branch Voltage, either a phase-to-phase voltage or a voltage across some power system component

BC - Branch Current, generally the current flowing through some power system component

TIME - time base for the case in question.

For data types BV and BC, the **name** component of the designator must be a name pair of the form **name1:name2**.

Whether the **name** is simple or compound (name pair), it must be unique within one case for any given data type. The permissible number of characters is installation dependent. Characters which serve as delimiters (i.e. blank, colon, semicolon, apostrophe, quote, equal sign, left and right parentheses, comma, and slash) should normally be avoided, since these characters usually require the use of delimiting quotes. The preferred set of characters consists of the alphanumerics, period, number sign ("#"), hyphen, underscore, ampersand, asterisk, and at sign ("@").

D. COMMANDS

Leading blanks on command lines are ignored. Commands may be abbreviated to any unambiguous short form. Commands are followed by one or more keyword parameters, separated from the command and other parameters by one or more blanks.

Keyword parameters may have values as appropriate. Where values have embedded blanks, the entire value must be enclosed in apostrophes or quotes. Embedded apostrophes within an apostrophe-delimited string must be doubled (also applies to quotes).

The general form of a command is

COMMAND **par1=value1 par2**

where

par1 is assigned value **value1**

par2 takes no value.

Some commands permit the use of designator lists, which are comprised of two or more designators separated by semicolons.

1. BATCH

The BATCH command indicates that operation is to be non-interactive. The TRP is set to abort on recognition of any error condition (ABEND-CODE=5). Command echoing is turned on.

This command takes no parameters.

Example:

```
BATCH
```

2. COMMENT

The COMMENT command provides a means of inserting comments into the TRP input. It has no effect on TRP operation.

The COMMENT command takes no parameters per se, but may be followed by any text.

Example:

```
COMMENT this is the comment text
```

3. COMPUTE

The COMPUTE command provides a means of manipulating existing waveforms and adding the result to the data area as a new waveform. This is by far the most powerful and flexible command, since it permits the user to invoke intrinsic TRP functions and optional user-created functions to create a custom waveform processor, or a custom simulator.

Because each COMPUTE operation is stand-alone, any feedback loops in simulated systems must be incorporated entirely within a single COMPUTE function.

The COMPUTE command takes a single keyword, which is the designator of the new entry to be generated. The "value" taken by this keyword is the name of the function to be invoked, immediately followed by a list of parameters to be "passed" to the function. The parameters are enclosed in parentheses. No blanks may appear between the function name and the parameter list.

If any of the parameters in the list (e.g. a name) has blanks in it, the entire keyword value (i.e. function name followed by parameter list) must be enclosed in apostrophes or quotes.

A list of intrinsic functions available through the COMPUTE command is given in a later section.

Example:

COMPUTE CV:SUM=ADD(CV:A,CV:B)

produces a new waveform of data type "CV", named "SUM", which is the addition (function ADD) of existing waveforms "CV:A" and "CV:B".

4. DELETE

The DELETE command provides a means of deleting data from the data area. The command takes three forms:

DELETE ALL

- this form deletes all data in the data area, and resets the TRP to the startup condition.

DELETE CASE=**case-number**

- this form deletes case **case-number.**

DELETE ENTRY=**designator-list**

- this form deletes entries associated with the designators in **designator-list.** The individual designators in a "designator list" are delimited from one another by semi-colons (e.g. CV:ONE;CV:TWO;CV:THREE).

Deletions do not actually occur until more data is added to the data area, or until the data is saved into an external file.

Where an entire case is deleted, subsequent (higher numbered) cases will be renumbered down during the data compaction stage which follows deletion (that is, when the data associated with the case is actually removed). A warning is issued when this occurs. Subsequent references to case numbers must take this renumbering into account. (The single exception is case 0, which may be deleted without resulting in case renumbering.)

Example:

DELETE ENTRY=CV:ONE;CV:TWO;CV:THREE

5. DISPLAY

The DISPLAY command permits the display of information from the data area. The specified information is written to the user terminal or TRP output file/device. Available items are:

CASE=**case-number**

- the title and entry names associated with case **case-number** are displayed on the user output device.

RANGE=**designator-list**

- the maximum and minimum values are displayed for each of the waveforms specified in the designator list **designator-list.** If more than one designator is given in the list, the overall maximum and minimum are also displayed.

VALUES(**start,stop,step**)=**designator**

- the values from the selected waveform are displayed on the user output device, starting with the point specified by **start** and ending with the point specified by **stop**, with points being displayed at steps of every **step** points (FORTRAN DO loop format). The numbers **start**, **stop**, and **step** represent integer (ordinal) positions within the waveform. For example, VALUES(23,46,2) would indicate the 23rd through 46th points, in steps of 2. The **start** and **step** values default to one, and the **stop** value defaults to the last point in the waveform.

AVERAGE(**start,stop**)=**designator**

- the average value of the waveform, or the portion thereof starting at **start** and ending at **stop**, is displayed on the user output device. The **start** value defaults to one and the **stop** value defaults to the last point in the waveform.

RMS(**start,stop**)=**designator**

- the RMS value of the waveform, or the portion thereof starting at

start and ending at **stop**, is displayed on the user output device. The **start** value defaults to one and the **stop** value defaults to the last point in the waveform.

HARMONICS(**start-time,base-freq,start-freq**)=**designator**

- the ten harmonics of a portion of the specified waveform starting at **start-time**, using a base frequency of **base-freq**, and starting with the harmonic at **start-freq**, are displayed on the user output terminal. The total extent of the waveform used for the harmonic analysis is one period of the base frequency, which defaults to the power system frequency. The start time and start frequency both default to zero.

Example:

DISPLAY RANGE=CV:ONE;CV:TWO;CV:THREE

6. GET

The GET command adds data from an external file to the data area. Two file formats are currently available:

EMTP=**study-identifier**

- The external file from which EMTP-written data is to be read must have a name starting with a "P", to which the **study-identifier** string has been appended. Since consecutive transient runs may be included in a single EMTP output ("plot") file, the file is kept open after the GET to permit the consecutive runs to be accessed through consecutive GETs with the same study identifier. The file is released only if RELEASE is included after the EMTP keyword parameter, or an end-of-file condition is detected.

TRP=**study-identifier**

- The external file from which the TRP-written data is to be read will have a name starting with a "D", to which the **study-identifier** string has been appended. This file must have been written by the TRP SAVE command.

The study identifier string is appended to an alphabetic character to form a file name (as indicated above), which of course must conform to rules (as to length, for example) appropriate to the host operating system. Thus the study identifier string selected must be chosen to ensure that the ultimate file name will conform to these rules.

The use of the study identifier string with a use-dependent prefix to form file names permits all files associated with a given simulation to be quickly located and identified.

Example:

GET EMTP=H09002 RELEASE

which causes the EMTP-written file *PH09002* to be accessed for a single simulation result (case) and then released.

7. PAUSE

The PAUSE command halts operation of the TRP and executes a FORTRAN PAUSE. The effect and usefulness of this command depends on the host operating system. For the command to be useful, the operating system requires the capability to restart halted programs.

This command takes no parameters.

Example:

PAUSE

8. PLOT

The PLOT command plots waveforms from the data area, from 1 to 6 traces ("channels") per page. Only the number of the trace position ("channel") to be used and the designator of the waveform to be plotted need be specified. Defaults are used for the other parameters to ensure acceptable plots. This provides complete freedom from plotting details, and maximizes ease of use. A full complement of control keywords are available to allow the plot details to be specified where this is preferable.

The available PLOT keywords are:

HOLD

- This keyword causes the plot page being generated to be held for a sequence of PLOT commands (between which other commands may be used). The plot page must subsequently be explicitly released for plotting, using the RELEASE keyword. The default action where HOLD has not been specified is to release the plot page after the single PLOT command has been completed.

RELEASE

- This keyword releases a plot page which has been explicitly held with the use of the HOLD keyword.

TRACES/PAGE=**n**

- This keyword specifies the number of plot traces which are to be formatted on a single page. The number **n** may range from one to six, inclusive. The default value, where this keyword is not specified, is six.

TITLE=**string** (or) * (or) **#n**

- This keyword specifies the title to be used for the plot. The **string** is any character string (limited to characters available for the ultimate plotting device), enclosed in quotes or apostrophes where blanks are used. The use of the asterisk character * specifies that the default title is to be used. The default title is the title of the case corresponding to the first plotted waveform.

The use of the sequence **#n**, where **n** is the case number, specifies that the title for case **n** is to be used as the plot title.

The plot title used where this keyword has not been specified is either the default title mentioned above, or the global plot title established with the TRP SET command (if one has been set).

The plot title may be up to 50 characters long. Longer titles will be truncated on the plot.

X-LABEL=**string** (or) Y-LABEL=**string**

- These keywords specify the text to be used as labels for the axes. Since there are up to six Y axes, one label may be specified for each trace. Where the label strings contain embedded blanks, the strings must be enclosed in quotes or apostrophes. The default labels are the designators of the plotted waveforms. The labels may be up to 50 characters long; longer labels are truncated on the plot.

X-UNITS=**string** (or) Y-UNITS=**string**

- These keywords specify the units to be used for the axes. Only fundamental units (e.g. Volts, Amps, seconds) should be specified, since the correct prefix (e.g. kilo, milli) will be prefixed automatically as part of the plot scaling procedure.

The default value for the units depends on the data type. The **CV** data type uses the string *UNITS*, since the actual unit is often arbitrary. Voltage data types (**BV**, **NV**) use the string *VOLTS*, while the current data type **BC** uses the string *AMPS*.

A null string (one or more blanks immediately to the right of the equal sign) may be specified, but this suppresses the scaling prefix also (since there is nothing to prefix to), and so should be used cautiously.

The units string may be up to 10 characters long; longer strings will be truncated on the plot.

X-SCALE=**scale-factor** (or) Y-SCALE=**scale-factor**

- These keywords specify scaling factors to be applied to the data prior to plotting. Thus a waveform which, for example, had been computed in volts, can be plotted in per unit. The default values of **scale-factor** are one.

X-RANGE=**(limit-1,limit-2)** (or) Y-RANGE=**(limit-1,limit-2)**

- These keywords specify the limits of the scales on the corresponding axes. The default action is to use the maximum and minimum data values, obtained by scanning the data. However the values are determined, the actual values used on the axes are rounded up according to internally-programmed rules which assure "nice" labels and steps between divisions.

The two limits need not be specified in any particular order, since they will be ordered internally.

TRACE(**trace-number**)=**y-dsg/x-dsg**

- This is the only keyword required for a plot. The traces on the plot page are numbered consecutively starting at one, located at the bottom of the page. The trace designated by **trace-number** is generated with data from **y-dsg** as the y-coordinate, and data from **x-dsg** as the x-coordinate. If **x-dsg** is not specified, the default action is to use the time base, which is the usual requirement.

More than one waveform may be included in a single trace. This feature, called **overlaying**, establishes the labels, units, and axis scaling from the first waveform. This should be kept in mind when determining the order of overlaying.

SYMBOLS/TRACE=**n**

- This keyword is of use during overlaying. The only assured means of distinguishing between overlays is by means of symbols which are included in the waveforms during plotting. (Where the plotting device has colour capability, the TRP PLOT routines also distinguish between overlays by using different colours.) The number of such symbols used is determined by **n.** The default value used when this parameter is not specified is generated by subtracting one from the overlay number. Thus the first overlay has no identifying symbol, the second has one, etc. The symbols used are determined by the plotter interface routines used.

The basic design of the PLOT command is such that all plot-formatting parameters for the various y axes are reset between PLOT command lines, even when the plot is being held. To permit the same y axis parameters to be used for more than one trace (and one overlay of that trace), a plot command may be continued by putting a hyphen at the end of the line to be continued, as the last non-blank character. Note that all plot-formatting parameters must be specified before the associated TRACE parameter is issued, so that ordinarily it is best to specify the TRACE parameters last. Note also that all plot-formatting parameters which determine the plot page layout (such as the title and number of traces per page) or the x-axis details (such as the x-axis label) must be specified before the first TRACE parameter. This is because a trace is produced as the last step after executing a PLOT command, before reading the next TRP input line, even when a PLOT command is being continued.

Example:

PLOT TRACES/PAGE=2 TRACE(1)=NV:WSN.A TRACE(2)=NV:WSN.B

9. SAVE

The SAVE command saves the present contents of the data area into an external file. Only one SAVE format is currently available:

TRP=**study-identifier**

The **study-identifier** string, described under the TRP command GET, is appended to the character "D" to form the name of the external file. Together, SAVE and GET using TRP format form a pair; the actual external file name is important only so far as the host operating system restrictions on legal file names affect the choice of **study-identifier** (as described under GET). Within the TRP, only study identifiers are used.

Example:

SAVE TRP=H09002

10. SET

The SET command sets global parameters for TRP operation. These parameters remain in effect only during a single TRP run—there is no memory between runs.

Parameters available are:

ABEND-CODE=**n**

- This parameter determines the value of TRP-generated "return codes" which will cause the TRP run to abort automatically. This feature is useful when the TRP is executing a prepared set of instructions; for truly interactive use the user is in full control.

Internal "return code" values greater than or equal to **n** cause the TRP to abort.

CASE-TITLE(**case-number**)=**string** (or) **#n**

- This parameter permits the case title to be set for case **case-number**. If the string to be used for the title includes blanks, the string must be delimited by apostrophes or quotes. The title can be duplicated from another case by using form **#n**, where **n** is the number of the case from which the title is to be copied. (Clearly, this precludes the use of a title string beginning with the character "#" unless the entire string is delimited by apostrophes or quotes.)

PLOT-TITLE=**string** (or) * (or) **#n**

- This parameter permits the default plot title to be set. The specifics of use are the same as for the TITLE parameter of the PLOT command.

FREQUENCY-BASE=**frequency**

- This parameter sets the TRP internal record of the power system frequency. The default value (at TRP startup) is 60 Hz.

ECHO=ON (or) OFF (or) **blank**

- This parameter controls echoing of TRP input lines. This feature is useful when the TRP is used in batch mode, or when the input commands are coming from an input file. If the keyword value is null (one or more **blanks** following the equal sign), rather than ON or OFF, the ECHO state is toggled (OFF to ON, or ON to OFF).

INPUT=**study-identifier** (or) *

- This parameter directs the TRP to take its input from another source. If **study-identifier** is given, the source is an external file with a name formed by prefixing the character "I" to **study-identifier**. The same considerations apply as were given under the GET command regarding choice of study identifiers. If an asterisk is specified rather than a study identifier, the input will be taken from the user input device, which is the input source assigned at TRP startup.

OUTPUT=**study-identifier** (or) *

- This parameter directs the TRP to send its output to another destination. If **study-identifier** is given, the destination is an external file with a name formed by prefixing the character "O" to **study-identifier**. The same considerations apply as were given under the GET command regarding choice of study identifiers. If an asterisk is specified rather than a study identifier, the output will be sent to the user output device, which is the output destination assigned at TRP startup.

MESSAGES=**study-identifier** (or) *

- This parameter directs the TRP to send its informational, warning, and error messages to another destination. If **study-identifier** is given, the destination is an external file with a name formed by prefixing the character "M" to **study-identifier**. The same considerations apply as were given under the GET command regarding choice of study identifiers. If an asterisk is specified rather than a study identifier, the messages will be sent to the user output device, which is the message destination assigned at TRP startup.

Example:

SET FREQUENCY-BASE=50 ABEND-CODE=5

11. STOP

The STOP command stops TRP execution and returns control to the host operating system using FORTRAN STOP **n**, where **n** is selected by the TRP to indicate a "return code" established by the TRP to flag the detection of errors. Return code values are 4 for warnings, 8 for errors which permit the TRP to continue execution, and 16 for errors which are fatal to continued TRP operation (the TRP will always abort in this latter case, sometimes gracelessly).

Where the value **n** is accessible by the host operating system, this feature can be used to facilitate conditional execution of operating system commands in a macro or batch mode (where the operating system offers this feature).

Example:

STOP

E. TRP INTERNAL FUNCTIONS

The TRP internal functions, accessed through the COMPUTE command, provide a basic set of waveform operations. The total set of available functions may be extended by adding user functions, as described in the next section.

All trailing scalar parameters for which default values are given may be omitted. Parameters may not be omitted between specified parameters; if one parameter is omitted, all following parameters must also be omitted.

The available internal functions are ADD, BASE, BLOCK, COPY, COSINE, GATE, INTEGRATE, MAXIMUM, MINIMUM, NEGATE, SUBTRACT, and ZERO-SEQUENCE, and are described following.

1. ADD

The ADD function adds two waveforms point by point; the sum is multiplied by an optional scaling factor.

The form of the TRP function invocation is:

COMPUTE **odsg**=ADD(**idsg-1**,**idsg-2**,**sclfct**)

where

odsg is the designator for the ADD result,

idsg-1 is the designator for one input,

idsg-2 is the designator for the second input,

sclfct is the factor by which the sum is to be scaled to produce the output waveform. The default value is one.

2. BASE

The BASE function generates a time base for a specified case; this feature is useful when the TRP is used to generate waveforms directly. The time base produced has a constant step size.

The form of the TRP function invocation is:

COMPUTE **odsg**=BASE(**stepsize**,**#-steps**)

where

odsg is the designator for the time base result, of the form **n**:TIME, where **n** is the case number,

stepsize is the size of the time steps, in seconds, and

#-steps is the number of time steps to be generated.

3. BLOCK

The BLOCK function "blocks" the path from the input through to the output if the control input is greater than zero. This is approximately equivalent to a normally-closed switch, except that the output is zero in the "blocked" (open) state.

The BLOCK function is the converse to the GATE function.

The form of the TRP function invocation is:

COMPUTE **odsg**=BLOCK(**idsg**,**idsg-C**)

where

odsg is the designator of the output waveform,

idsg is the designator of the waveform to be controlled, and

idsg-C is the designator of the controlling waveform.

4. COPY

The COPY function permits a scaled copy of a waveform to be produced. COPY is helpful when accounting for CT and VT ratios in protection simulations where actual CT and VT models are not used.

The form of the TRP function invocation is:

COMPUTE **odsg**=COPY(**idsg**,**sclfct**)

where

odsg is the designator of the output waveform,

idsg is the designator of the input waveform, and

sclfct is the scaling factor applied during the copy. The default value is one.

5. COSINE

The COSINE function permits the generation of a pure cosine waveform of specified amplitude, phase, and frequency.

The form of the TRP function invocation is:

COMPUTE **odsg**=COSINE(**case**,**magn**,**phase**,**freq**)

where

odsg is the designator of the output waveform,

case is the number of the case from which the time base is to be used to generate the cosine (usually the same as the case to which **odsg** belongs).

magn is the magnitude of the resulting cosine. The default value is one.

phase is the phase angle of the resulting cosine, in degrees. The default value is zero.

freq is the frequency of the resulting cosine, in Hertz. The default value is the power system frequency.

6. GATE

The GATE function "gates" the input to the output if the control input is greater than zero. This is approximately equivalent to a normally-open switch, except that the output is zero in the "ungated" (open) state.

The GATE function is the converse to the BLOCK function.

The form of the TRP function invocation is:

COMPUTE **odsg**=GATE(**idsg**,**idsg-C**)

where

odsg is the designator of the output waveform,

idsg is the designator of the waveform to be controlled, and

idsg-C is the designator of the controlling waveform.

7. INTEGRATE

The INTEGRATE function produces a running integral of the input waveform, starting from a specified initial condition at the first point. A gain can also be specified, permitting the output to be scaled. The numerical technique used is trapezoidal integration.

The form of the TRP function invocation is:

COMPUTE **odsg**=INTEGRATE(**idsg**,**gain**,**ic**)

where

odsg is the designator of the output waveform,

idsg is the designator of the input waveform,

gain is the gain (scale factor) to be used for the integration. The default value is one.

ic is the initial condition to be used at the start of integration. The default value is zero.

8. MAXIMUM

The MAXIMUM function produces a result which is the point-by-point maximum of two input waveforms. If desired, an index can be produced which gives a measure of the amount by which the resultant waveform differs from the first of the two specified input waveforms. This index is the RMS difference between the first waveform and the result.

The form of the TRP function invocation is:

COMPUTE **odsg**=MAXIMUM(**idsg-1**,**idsg-2**,**cindex**)

where

odsg is the designator of the output waveform,

idsg-1 is the designator of one input waveform,

idsg-2 is the designator of the second input waveform, and

cindex is a value for controlling the computation of the RMS index. If **cindex** is positive the index is computed and displayed. The default value of **cindex** is negative, for no index.

9. MINIMUM

The MINIMUM function produces a result which is the point-by-point minimum of two input waveforms. If desired, an index can be produced which gives a measure of the amount by which the resultant waveform differs from the first of the two specified input waveforms. This index is the RMS difference between the first waveform and the result.

The form of the TRP function invocation is:

COMPUTE **odsg**=MINIMUM(**idsg-1**,**idsg-2**,**cindex**)

where

odsg is the designator of the output waveform,

idsg-1 is the designator of one input waveform,

idsg-2 is the designator of the second input waveform,

cindex is a value for controlling the computation of the RMS index. If **cindex** is positive the index is computed and displayed. The default value of **cindex** is negative, for no index.

10. NEGATE

The NEGATE function provides a simple algebraic negation of the input waveform.

The form of the function invocation in the TRP is:

COMPUTE **odsg**=NEGATE(**idsg**)

where

odsg is the designator for the output.

idsg is the designator for the input.

11. SUBTRACT

The SUBTRACT function subtracts one waveform from another point by point; the difference is multiplied by an optional scaling factor.

The form of the TRP function invocation is:

COMPUTE **odsg**=SUBTRACT(**idsg-1**,**idsg-2**,**sclfct**)

where

odsg is the designator for the result,

idsg-1 is the designator for one input,

idsg-2 is the designator for the second input,

sclfct is the factor by which the difference is to be scaled to produce the output waveform. The default value is one.

12. ZERO-SEQUENCE

The ZERO-SEQUENCE function computes the zero-sequence component of three input waveforms. The result has meaning only where the input waveforms are the three phase components of a single three-phase quantity (e.g. voltage).

The form of the TRP function invocation is:

COMPUTE **odsg**=ZERO-SEQUENCE(**idsg-A**,**idsg-B**,**idsg-C**)

where

odsg is the designator for the zero-sequence output waveform,

idsg-A is the designator for the phase A component,

idsg-B is the designator for the phase B component, and

idsg-C is the designator for the phase C component

of the input quantity.

F. PREPARING AND INTERFACING TRP USER FUNCTIONS

TRP user functions are best prepared by first writing a self-contained FORTRAN-callable subroutine which takes as parameters all required settings and input values, and returns as parameters the necessary vector outputs. The length of the input and output vectors is equal to the number of time steps, which is available as a parameter from the TRP interface routine.

The TRP interface skeleton TRPUFX, listed in fig. 39, provides a

```
Listing of TRPUFX.F77 at 01:16:25 on MAY  9, 1986 for CCid=BRWG                                    Page     1

      SUBROUTINE TRPUFX(RESULT, NELMNT, NDATA, DATA, MDATA,
     1           PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
     2           NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
C     *** FORTRAN 77 ***
C
C     Purpose: prototype user function
C
C *** Constant parameters:
C
      INTEGER SIDATE, DPARMS
      CHARACTER*(*) SBNAME
C
C *** Start of user change ****************************************
C ***            --change SIDATE to date of routine creation      *
C ***            --change SBNAME to name of subroutine            *
C ***            --change DPARMS to number of designators required  *
      PARAMETER (SIDATE=19860210,SBNAME='TRPUFX',DPARMS=1)
C *** End of user change ******************************************
C
C     DPARMS: number of designator parameters required
C     SBNAME: routine name
C     SIDATE: SI form of date of last change to this routine.
C
C *** General variables:
C
      INTEGER SDATE, NDATA, NELMNT, MDATA, NPARMS, INDX(DPARMS),
     1        ICASE(DPARMS), DTYPE(DPARMS), NVPEL,
     2        IELMNT(DPARMS), ITYPE(*), NCODES, ISTART(*), IEND(*
     3        ), IBASE(DPARMS), NENTRY, CODES(*), DSTART(DPARMS),
     4        DEND(DPARMS)
      REAL DATA(*), RESULT(*), SETVLU(*)
      LOGICAL LABORT
      CHARACTER*(*) PARMS(*),NAMES(2,*),KEYS(*)
C
C     CODES:  List of data type codes (input)
C     DATA:   Data for database (input/output)
C     DEND:   list of ending pointers to data in database
C     DSTART: list of starting pointers to data in database
C     DTYPE:  List of type codes for entries
C     IBASE:  List of indicies for bases for entries
C     ICASE:  List of case numbers for entries
C     IELMNT: List of elements for entries
C     IEND:   List of ending locations for database entries (input)
C     INDX:   List of indicies for entries
C     ISTART: List of starting locations for database entries (input)
C     ITYPE:  List of data types for database entries (input)
C     KEYS:   List of data type keys (input)
C     LABORT: true if routine aborts (output)
C     MDATA:  Maximum number of locations in database (input)
C     NAMES:  List of names for database entries (input)
C     NCODES: Number of data type codes (input)
C     NDATA:  Number of data values in database (input/output)
C     NELMNT: Number of elements being created (output)
C     NENTRY: Number of entries in database (input)
C     NPARMS: Number of parameters being passed (input)
C     NVPEL:  Number of data values per element

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 39. Listing of skeleton TRPUFX

```
Listing of TRPUFX.F77 at 01:16:25 on MAY  9, 1986 for CCid=BRWG                                   Page    2

      C      PARMS:  List of parameters being passed (input)
      C      RESULT: Result of computation (output)
      C      SDATE:  Set non-zero if routine date has already been passed
      C                    to NVDATE.
      C      SETVLU: various TRP settings (input)
      C
      C *** External routines:
      C
             INTEGER NVDATE
      C
      C      ERRMSG: sends error message to user
      C      NVDATE: Version dating routine. First parameter is SI
      C                    date, second is "version group" number of this
      C                    subprogram.
      C      TRCBAK: keeps subroutine traceback list
      C      UFAUX:  auxiliary routine for user functions to:
      C                    - get pointers etc for parameter designators
      C                    - check that data have matching time bases
      C                    - ensure that database has enough room for data
      C
      C
      C *** User variables ******************************************
      C
      C      INTEGER
      C      REAL
      C      DOUBLE PRECISION
      C      COMPLEX
      C      LOGICAL
      C      CHARACTER
      C
      C
      C *** End of user variables ***************************************
      C
      C *** User external routines **************************************
      C
      C      INTEGER
      C      REAL
      C      DOUBLE PRECISION
      C      COMPLEX
      C      LOGICAL
      C      EXTERNAL,
      C
      C
      C *** End of user external routines *******************************
      C
             DATA SDATE /0/
             SAVE SDATE
      C -------------------------------------------------- *** START ***
      C      Pass routine date to NVDATE if not done already.
             IF (SDATE .EQ. 0) SDATE = NVDATE(SIDATE,2)
             CALL TRCBAK(SBNAME,1)
      C
      C *** Start of user change ****************************************
      C ***                      --change value of NELMNT to number of     *
      C ***                          waveforms which will result from      *
      C ***                          function                              *

         .........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 39 (cont'd)

```
Listing of TRPUFX.F77 at 01:16:25 on MAY  9, 1986 for CCid=BRWG                                    Page    3

      C       constant:
              NELMNT = 1
      C *** End of user change ******************************************
      C
      C       check for required number of parameters
              LABORT = NPARMS .LT. DPARMS
              IF (LABORT) THEN
      C
      C *** Start of user change ****************************************
      C ***                       --change error message to reflect        *
      C ***                           number of entries required           *
                 CALL ERRMSG(SBNAME, 'Exactly 0 parameters are required',
           1           2)
      C *** End of user change ******************************************
      C
      C          GO TO is "ABORT"
                 GO TO 1000
              END IF
      C
      C       get pointers and make standard checks
              CALL UFAUX(INDX, ICASE, DTYPE, DSTART, DEND, IELMNT, IBASE,
           1      NVPEL, LABORT, NDATA, DATA, MDATA, PARMS, DPARMS,
           2      ISTART, IEND, ITYPE, NAMES, NENTRY, CODES, KEYS,
           3      NCODES, NELMNT)
      C       GO TO is "ABORT"
              IF (LABORT) GO TO 1000
      C
      C *** User code to recover parameters follows ****************
      C *** End of user code to recover parameters *****************
      C
      C *** User code to compute function follows ******************
              DO 10 I = 0, NVPEL - 1
                 RESULT(I + 1) = 0.0
           10 CONTINUE
      C *** End of user code to compute function ******************
      C
      1000  CALL TRCBAK(' ',-1)
              RETURN
              END

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 39 (cont'd)

relatively simple method of interfacing the stand-alone subroutine just described with the TRP. The second stage in the interfacing process is to modify the TRPUFX skeleton as required to get the required interface subroutine.

The modification procedure, which will be described now, can be most easily followed by referring to the TRPUFX skeleton in fig. 39 and an example interface routine UFTIMR (for the delayed-pickup/delayed-dropout timer model described in appendix B) listed in fig. 40.

The first step is to change the subroutine name to something unique and more-or-less descriptive (TRPUFX lines 1 and 17; UFTIMR lines 14001 and 14016). (The parameter SBNAME at TRPUFX line 17 and UFTIMR line 14016 is used to maintain a "traceback" list within the TRP in case of errors.) It is wise to use "UF" as the first two characters of interface routine names to prevent conflict with other names, and to allow them to be easily identified as interface routines. It is also helpful at this step to enter a description of the purpose of the function (TRPUFX line 6; UFTIMR line 14006).

The next step is to set the last-modification date for the routine as parameter SIDATE (TRPUFX line 17; UFTIMR line 14016). This date is used to maintain a dynamic "version date" within the TRP, which reflects the TRP version represented by the subroutines actually invoked. This date is kept in SAVE files and is printed at TRP termination.

The parameter DPARMS (TRPUFX line 17; UFTIMR line 14016) should now be changed to reflect the number of designator parameters required by the ultimate function. This information is used for storage allocation within the interface routine. The example timer model requires only one designator (for the timer start/stop control input).

```
Listing of TRPUF1.F77(14001,15000) at 01:16:27 on MAY  9, 1986 for CCid=BRWG                                Page    1

      SUBROUTINE UFTIMR(RESULT, NELMNT, NDATA, DATA, MDATA,
     1            PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
     2            NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
C      *** FORTRAN 77 ***
C
C     Purpose: timer model
C
C *** Constant parameters:
C
      INTEGER SIDATE, DPARMS
      CHARACTER* (*) SBNAME
C *** Start of user change *****************************************
C ***             --change SIDATE to date of routine creation **********
C ***             --change SBNAME to name of subroutine ****************
C ***    ,        --change DPARMS to number of designators required ****
      PARAMETER (SIDATE=19860227,SBNAME='UFTIMR',DPARMS=1)
C *** End of user change *******************************************
C
C     DPARMS: number of designator parameters required
C     SBNAME: routine name
C     SIDATE: SI form of date of last change to this routine.
C
C *** General variables:
C
      INTEGER SDATE, NDATA, NELMNT, MDATA, NPARMS, INDX(DPARMS),
     1        ICASE(DPARMS), DTYPE(DPARMS), NVPEL,
     2        IELMNT(DPARMS), ITYPE(*), NCODES, ISTART(*), IEND(*
     3        ), IBASE(DPARMS), NENTRY, CODES(*), DSTART(DPARMS),
     4        DEND(DPARMS)
      REAL DATA(*), RESULT(*), SETVLU(*)
      LOGICAL LABORT
      CHARACTER* (*) PARMS(*), NAMES(2,*), KEYS(*)
C
C     CODES:  List of data type codes (input)
C     DATA:   Data for database (input/output)
C     DEND:   list of ending pointers to data in database
C     DSTART: list of starting pointers to data in database
C     DTYPE:  List of type codes for entries
C     IBASE:  List of indicies for bases for entries
C     ICASE:  List of case numbers for entries
C     IELMNT: List of elements for entries
C     IEND:   List of ending locations for database entries (input)
C     INDX:   List of indicies for entries
C     ISTART: List of starting locations for database entries (input)
C   * ITYPE:  List of data types for database entries (input)
C     KEYS:   List of data type keys (input)
C     LABORT: true if routine aborts (output)
C     MDATA:  Maximum number of locations in database (input)
C     NAMES:  List of names for database entries (input)
C     NCODES: Number of data type codes (input)
C     NDATA:  Number of data values in database (input/output)
C     NELMNT: Number of elements being created (output)
C     NENTRY: Number of entries in database (input)
C     NPARMS: Number of parameters being passed (input)
C     NVPEL:  Number of data values per element
C     PARMS:  List of parameters being passed (input)

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 40. Listing of example interface routine UFTIMR

```
Listing of TRPUF1.F77(14001,15000) at 01:16:27 on MAY  9, 1986 for CCid=BRWG                                   Page    2

      C      RESULT: Result of computation (output)
      C      SDATE:  Set non-zero if routine date has already been passed
      C                    to NVDATE.
      C      SETVLU: various TRP settings (input)
      C
      C *** External routines:
      C
             INTEGER NVDATE
      C
      C      ERRMSG: sends error message to user
      C      NVDATE: Version dating routine. First parameter is SI
      C                    date, second is "version group" number of this
      C                    subprogram.
      C      TRCBAK: keeps subroutine traceback list
      C      UFAUX:  auxiliary routine for user functions to:
      C                    - get pointers etc for parameter designators
      C                    - check that data have matching time bases
      C                    - ensure that database has enough room for data
      C
      C
      C *** User variables ******************************************
      C
             REAL IC, PUDLY, DODLY, VLIM
             LOGICAL LREAL
      C
      C      DODLY:  drop-out delay
      C      IC:     initial condition for timer (high if IC > 0)
      C      LREAL:  true if string is real number
      C      PUDLY:  pickup delay
      C      VLIM:   limit for output range
      C
      C *** End of user variables ***********************************
      C
      C  *** User external routines ****************************************
      C
      C      INTPNB: tries to interpret string as real number
      C      TIMER:  simulates delayed pickup/dropout timer
      C
      C *** End of user external routines **********************************
      C
             DATA SDATE /0/
             SAVE SDATE
      C ---------------------------------------------------- *** START ***
      C      Pass routine date to NVDATE if not done already.
             IF (SDATE .EQ. 0) SDATE = NVDATE(SIDATE,2)
             CALL TRCBAK(SBNAME, 1)
      C
      C      constant:
      C *** Start of user change ******************************************
      C ***                        --change value of NELMNT to number of
      C ***                            waveforms which will result from
      C ***                            function ******************************
      C      specify one extra element for temporary storage
             NELMNT = 2
      C *** End of user change ********************************************
      C

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 40 (cont'd)

```
Listing of TRPUF1.F77(14001,15000) at 01:16:27 on MAY  9, 1986 for CCid=BRWG                                Page    3

      C     check for required number of parameters
            LABORT = NPARMS .LT. DPARMS
            IF (LABORT) THEN
      C *** Start of user change ***************************************
      C ***                        --change error message to reflect
      C ***                             number of entries required
               CALL ERRMSG(SBNAME, 'At least 1 parameter is required',
           1         2)
      C *** End of user change *********************************************
      C        GO TO is "ABORT"
               GO TO 10
            END IF
      C
      C     get pointers and make standard checks
            CALL UFAUX(INDX, ICASE, DTYPE, DSTART, DEND, IELMNT, IBASE,
           1     NVPEL, LABORT, NDATA, DATA, MDATA, PARMS, DPARMS,
           2     ISTART, IEND, ITYPE, NAMES, NENTRY, CODES, KEYS,
           3     NCODES, NELMNT)
      C     GO TO is "ABORT"
            IF (LABORT) GO TO 10
      C
      C *** User code to recover parameters follows ****************
      C     constants:
            VLIM = 10.0
      C
      C     defaults:
            IC = -VLIM
            PUDLY = 0.0
            DODLY = 0.0
            IF (NPARMS .GE. 2) THEN
               CALL INTPNB(PUDLY, PARMS(2), LREAL)
               LABORT = .NOT. LREAL .OR. PUDLY .LT. 0.0
               IF (LABORT) THEN
                  CALL ERRMSG(SBNAME, 'Bad value for pickup delay', 2)
               ELSE IF (NPARMS .GE. 3) THEN
                  CALL INTPNB(DODLY, PARMS(3), LREAL)
                  LABORT = .NOT. LREAL .OR. DODLY .LT. 0.0
                  IF (LABORT) THEN
                     CALL ERRMSG(SBNAME, 'Bad value for dropout delay',
           1              2)
                  ELSE IF (NPARMS .GE. 4) THEN
                     CALL INTPNB(IC, PARMS(4), LREAL)
                     LABORT = .NOT. LREAL .OR. IC .LT. 0.0
                     IF (LABORT) CALL ERRMSG(SBNAME, 'Bad value for IC'
           1              , 2)
                  END IF
               END IF
            END IF
      C     GO TO is ABORT
            IF (LABORT) GO TO 10
      C
      C *** End of user code to recover parameters *****************
      C
      C *** User code to compute function follows ******************
            CALL TIMER(RESULT,RESULT(NVPEL+1),DATA(DSTART(1)),DATA(ISTA
           1RT(IBASE(1))),NVPEL, PUDLY, DODLY, IC, VLIM)

  .       .........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 40 (cont'd)

```
      C *** End of user code to compute function *******************
      C
      C     remove extra element now to free storage
         10 NELMNT = 1
            NDATA = NDATA - NVPEL
            CALL TRCBAK(' ', -1)
            RETURN
            END
```

```
.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 40 (cont'd)

The next step is to define any user variables or external routines which will be required within the interface routine (TRPUFX lines 78-100; UFTIMR lines 14077-14095). (The function INTPNB at UFTIMR line 14092 is a stock TRP function which is useful when decoding constant parameters.)

The next step is to specify the number of elements needed in the output vector, via NELMNT (TRPUFX line 114; UFTIMR line 14110). In the example routine UFTIMR, the number of elements has been set high by one, in order to force the TRP to get extra storage for temporary use. This storage has been released again at lines 14172-3. Only the *highest numbered contiguous* elements can be released, so these are the ones to use for temporary storage (element 2 in the example).

It is now necessary to change the error message produced when insufficient parameters have been given (TRPUFX line 124; UFTIMR line 14119). Ordinarily only designators are required parameters, the others taking default values when not specified.

The next step is to specify the instructions to recover any scalar parameters (the routine UFAUX at TRPUFX line 133 automatically handles designators, which are always specified as the first parameters in the function parameter list), between TRPUF lines 140-1. This is done as shown for the UFTIMR example routine at lines 14134-64.

Finally, the code to compute the function must be added, replacing the dummy lines 144-6 in TRPUFX. This generally consists of a call to the self-contained subroutine prepared earlier, perhaps with some preparatory computations.

For the UFTIMR example routine, only a call was required (at lines

14167-8). The output waveforms are interfaced to the two elements stored sequentially in RESULT. The number of values (time steps) in each element is available from NVPEL. This is used here both for specifying the length of the input and output vectors, and for computing the offset of the second (and subsequent) elements in RESULT. (Full advantage is taken here of the superior and now-standard "pass-by-location" method of parameter reference in FORTRAN 77 parameter lists.)

The input waveforms are taken directly from the data area DATA, using starting locations in DSTART. The time base (where required) for each input waveform is accessed by using the corresponding element of IBASE to address the data area through the indexing vector ISTART, as shown at UFTIMR lines 14167-8.

The significance of the entries in the TIMER parameter list is:

RESULT: output waveform in element 0,

RESULT(NVPEL+1): temporary storage in element 1,

DATA(DSTART(1)): input waveform for timer on/off control,

DATA(ISTART(IBASE(1))): time base for case corresponding to input waveform,

NVPEL: number of time steps per waveform, equal to the number of values per element,

PUDLY: timer pickup delay,

DODLY: timer dropout delay,

IC: initial condition for timer on/off status, and

VLIM: output-range limit for timer.

The third and final stage in the interfacing process is to include the function name in the routine which calls the interface routine from the TRP. A special TRP routine, TRPUFN, has been prepared for this purpose. The initial form of this routine has no subroutine calls; the calls are added as user functions are added. A "mature" form of this routine, developed for the user functions described in appendix B, is listed in fig. 41.

The function name taken from the COMPUTE command is contained in FNCTN (e.g. line 5084). The name in FNCTN is tested against valid function names in an extended IF-ELSEIF instruction. The form of the entries can be seen from lines 5150-4, for example, which provide the call to the subroutine UFTIMR described earlier. The function list in TRPUFN is scanned *before* the list of TRP internal functions, so that user-functions may replace internal functions of the same name.

G. TRP FILE PREFIXES

All files used by the TRP have names beginning with a TRP-specified prefix which depends on the use to which the file is put. The remainder of the file name consists of a "study identifier" string specified in TRP commands. The file prefix is assigned according the the list in table 4.

```
Listing of TRPUF1.F77(5001,6000) at 01:16:25 on MAY  9, 1986 for CCid=BRWG                              Page    1

      SUBROUTINE TRPUFN(LNFND, RESULT, NELMNT, NDATA, DATA,
     1           MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND,
     2           NAMES, NENTRY, CODES, KEYS, NCODES, SETVLU,
     3           LABORT, FNCTN)
C     *** FORTRAN 77 ***
C
C     Purpose: Recognizes user function name, and calls
C              appropriate routine
C
C *** Constant parameters:
C
      INTEGER SIDATE
      CHARACTER* (*) SBNAME
      PARAMETER (SIDATE=19860326,SBNAME='TRPUFN')
C
C     SBNAME: routine name
C     SIDATE: SI form of date of last change to this routine.
C
C *** General variables:
C
      INTEGER SDATE, NDATA, NELMNT, MDATA, NPARMS, CODES, NCODES,
     1        ITYPE(*), ISTART(*), IEND(*), NENTRY
      REAL DATA(*), SETVLU(*), RESULT(*)
      LOGICAL LABORT, LNFND
      CHARACTER* (*) FNCTN, PARMS(*), KEYS(*), NAMES(2,*)
C
C     CODES:  Data type codes (input)
C     DATA:   Data for database (input/output)
C     FNCTN:  Function name (input)
C     IEND:   List of ending locations for database entries (i/o)
C     ISTART: List of starting locations for database entries (i/o)
C     ITYPE:  List of data types for database entries (input/output)
C     KEYS:   Data type keys (input)
C     LABORT: true if function call has aborted (output)
C     LNFND:  true if function name has not been identified
C                in this routine (output)
C     MDATA:  Maximum number of locations in database (input)
C     NAMES:  Name list for database entries (input)
C     NCODES: Number of data type codes (input)
C     NDATA:  Number of data values in database (input/output)
C     NELMNT: Number of elements in function output(i/o)
C     NENTRY: Number of entries in database (input/output)
C     NPARMS: Number of parameters found in function parm. list
C             (input)
C     PARMS:  Parameters from function designator (input)
C     RESULT: result from function (output)
C     SDATE:  Set non-zero if routine date has already been passed
C                to NVDATE.
C     SETVLU: various settings for TRP (input)
C
C *** External routines:
C
      INTEGER NVDATE
C
C     ERRMSG: sends error message to user
C     NVDATE: Version dating routine. First parameter is SI

       .........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2
```

Fig. 41. Listing of example of completed routine TRPUFN

```
C                date, second is "version group" number of this
C                subprogram.
C       TRCBAK: keeps subroutine traceback list
C       TRPBLK: blocks first waveform by second, point by point
C       TRPCAR: converts polar representation back to Cartesian form.
C       TRPGAT: gates first waveform by second, point by point
C       TRPLVL: shifts level of waveform by constant amount, point by
C               point
C       TRPPLR: converts two waveforms into polar representation, first
C                is taken as X, second as Y, result is two-element
C                vector, with first element being radius, second angle.
C                **** base has no meaning. ****
C       UFNEG:  negates specified entry
C       UFOCR:  restrained overcurrent relay
C       UFPSFA: positive sequence filter, type A
C       UFPTA:  permissive trip block, type A
C       UFTIMR: delayed pickup/dropout timer
C
        DATA SDATE /0/
        SAVE SDATE
C ----------------------------------------------------- *** START ***
C       Pass routine date to NVDATE if not done already.
        IF (SDATE .EQ. 0) SDATE = NVDATE(SIDATE,2)
        CALL TRCBAK(SBNAME, 1)
C
C       Identify function and call appropriate routine
        LNFND = .FALSE.
        IF (FNCTN .EQ. 'DELAY') THEN
C          delay unit--uses "pass by location"
           CALL TRPUF7(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
     1          MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
     2          NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
        ELSE IF (FNCTN .EQ. 'GATE') THEN
C          gate first waveform by second--uses "pass by location"
           CALL TRPGAT(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
     1          MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
     2          NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
        ELSE IF (FNCTN .EQ. 'BLOCK') THEN
C          block first waveform by second--uses "pass by location"
           CALL TRPBLK(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
     1          MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
     2          NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
C       ELSE IF (FNCTN .EQ. 'LEVEL-SHIFT') THEN
C           shifts level of waveform by constant amount--uses "pass by
C            location"
C          CALL TRPLVL(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
C    1          MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
C    2          NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
C       ELSE IF (FNCTN .EQ. 'POLAR') THEN
C          converts two waveforms into polar representation. First
C            is taken as X, second as Y, result is two-element vector,
C            first is radius, second is angle--uses "pass by location"
C          CALL TRPPLR(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
C    1          MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
C    2          NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
C       ELSE IF (FNCTN .EQ. 'CARTESIAN') THEN

........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 41 (cont'd)

```
Listing of TRPUF1.F77(5001,6000) at 01:16:25 on MAY  9, 1986 for CCid=BRWG                                                Page    3

      C          converts polar representation back into Cartesian form. First
      C            element is X, second is Y (result is two-element vector).
      C            For input, first element is radius, second is angle
      C            Uses "pass by location"
      C          CALL TRPCAR(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
      C     1         MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
      C     2         NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
              ELSE IF (FNCTN .EQ. 'OVERCURRENT.R') THEN
      C          restrained over-current relay--uses "pass by location"
                 CALL UFOCR(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
            1         MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
            2         NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
              ELSE IF (FNCTN .EQ. 'NEGATE' .OR. FNCTN .EQ. 'NOT') THEN
      C          negate specified entry--uses "pass by location"
                 CALL UFNEG(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
            1         MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
            2         NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
              ELSE IF (FNCTN .EQ. 'OVERCURRENT.IT') THEN
      C          inverse time over-current relay--uses "pass by location"
                 CALL TRPUF1(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
            1         MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
            2         NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
              ELSE IF (FNCTN .EQ. 'PS-FILTER.A') THEN
      C          positive sequence filter type A--uses "pass by location"
                 CALL UFPSFA(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
            1         MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
            2         NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
              ELSE IF (FNCTN .EQ. 'SD2H') THEN
      C          Westinghouse SD-2H relay--uses "pass by location"
                 CALL UFSD2H(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
            1         MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
            2         NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
              ELSE IF (FNCTN .EQ. 'SDX1H') THEN
      C          Westinghouse SDX-1H relay--uses "pass by location"
                 CALL UFSDXH(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
            1         MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
            2         NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
              ELSE IF (FNCTN .EQ. 'TIMER') THEN
      C          delayed pickup/dropout timer--uses "pass by location"
                 CALL UFTIMR(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
            1         MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
            2         NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
              ELSE IF (FNCTN .EQ. 'UNDERVOLTAGE') THEN
      C          undervoltage relay--uses "pass by location"
                 CALL TRPUF2(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
            1         MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
            2         NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
              ELSE IF (FNCTN .EQ. 'OVERVOLTAGE.NS') THEN
      C          negative sequence relay--uses "pass by location"
                 CALL TRPUF3(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
            1         MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
            2         NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
      C       ELSE IF (FNCTN .EQ. 'USER-4') THEN
      C          user # 4--uses "pass by location"
      C          CALL TRPUF4(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
      C     1         MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,

         .........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.
```

Fig. 41 (cont'd)

```
C    2         NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
           ELSE IF (FNCTN .EQ. 'POLARIZED-MHO.B') THEN
C             polarized mho (type B) relay--uses "pass by location"
              CALL TRPUF5(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
     1             MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
     2             NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
           ELSE IF (FNCTN .EQ. 'LAC') THEN
C             load angle compensator (series tuned transactor)
C                 uses "pass by location"
              CALL UFLAC(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
     1             MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
     2             NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
           ELSE IF (FNCTN .EQ. 'MEMORY' .OR. FNCTN .EQ. 'FILTER') THEN
C             memory or RLC filter--uses "pass by location"
              CALL TRPUF8(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
     1             MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
     2             NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
           ELSE IF (FNCTN .EQ. 'DIRECTIONAL') THEN
C             directional element--uses "pass by location"
              CALL TRPUF9(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
     1             MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
     2             NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
           ELSE IF (FNCTN .EQ. 'PERMISSIVE') THEN
C             permissive trip block type A--uses "pass by location"
              CALL UFPTA(DATA(ISTART(NENTRY)), NELMNT, NDATA, DATA,
     1             MDATA, PARMS, NPARMS, ITYPE, ISTART, IEND, NAMES,
     2             NENTRY, CODES, KEYS, NCODES, SETVLU, LABORT)
           ELSE
C             function name not recognized--not user function
              LNFND = .TRUE.
C             LABORT not assigned since no calls were made, so:
              LABORT = .FALSE.
           END IF
C
        10 CALL TRCBAK(' ', -1)
           RETURN
           END
```

.........1.........2.........3.........4.........5.........6.........7.........8.........9.........0.........1.........2.

Fig. 41 (cont'd)

TABLE 4

Prefix List for TRP Files

Prefix	File Use
I	command input file (SET INPUT= . . .)
O	output log file (SET OUTPUT= . . .)
M	messages file (SET MESSAGES= . . .)
P	EMTP-generated data file (GET EMTP= . . .)
D	TRP-format SAVE file (SAVE/GET TRP= . . .)

H. TRP DESIGN LIMITS

The design limits for the TRP are shown in table 5. Installation limits apply on the memory allocated to the TRP and on lengths of names, number of cases, etc., which will determine the actual practical limits.

TABLE 5

TRP Design Limits

Limit	Value
Maximum number of cases	2148
Maximum number of data types	8999
Maximum number of elements per waveform vector	100
Maximum number of base types	1000
Maximum length of PLOT UNITS string (characters)	10
Maximum length of PLOT LABELS string (characters)	50
Maximum length of PLOT TITLE string (characters)	50