MULTILIN

GER-3055

GE Power Management

Consideration of Speed, Dependability, and Security in Pilot Relaying Schemes

CONTENTS

CONSIDERATIONS OF SPEED, DEPENDABILITY, AND SECURITY IN HIGH-SPEED PILOT RELAYING SCHEMES

by

Joseph G. Andrichak and Stanley B. Wilkinson

Electric Utility Application Engineers
Power Systems Business Department
General Electric Co., Philadelphia, Pa. 19142

A high speed pilot relaying scheme should be designed so that an optimum balance of speed, dependability and security is obtained. The following must be considered:

1. The needs of the power system and the relaying speed required to meet those needs.

2. The transients introduced by the system and associated equipment during system disturbances; and the effect of these transients on relay design and performance.

3. Relay characteristics, relaying schemes and relaying channels.

It is the purpose of this paper to discuss these factors and to show how they are considered in providing an optimum balance of speed, dependability and security in a relaying scheme that will meet the needs of the system.

SYSTEM CONSIDERATIONS AND RELAYING SPEED

It is necessary to consider the needs of the system before the speed required from a relaying scheme can be realistically specified. The system shown in Figure 1 was examined to show how transient stability, usually the main criteria, can be used for determining the relaying speed requirements. The effects of different fault types, fault locations and system parameters were studied for the following systems having the configuration shown in Figure 1.

1. Long lines, strong sources

2. Short lines, weak sources

3. Short line paralleled by a weak interconnection

Specific details of the studies are given in Appendix I, which can be referred to by the reader if desired. The main points to be noted are as follows:

A. At any given fault location, three-phase faults are the most serious threat to stability while single-phase-to-ground faults are the least serious. Double-phase-to-ground and double-phase faults fall somewhere in between, in that order.

B. A three-phase fault at either terminal of one of two parallel transmission lines is more serious than a three-phase fault at any other location because no power can be transmitted across either line. During faults at locations other than the terminals of one of the lines, some power can still be transmitted across the unfaulted line, with this power becoming greatest for faults near the center of the faulted line. Since the stability margin will be increased as the ability to transfer power increases, somewhat longer relaying times can be tolerated for faults near the center of the line, particularly for long lines where the line impedance will be effective in decreasing the severity of the fault. On short lines the severity of the fault is almost independent of fault location because of the insignificance of the line impedance and it is imperative that clearing be initiated rapidly for three-phase faults anywhere on these lines. On long lines, it is only necessary to clear the fault quickly at the terminal near the fault. Longer clearing times can then be tolerated at the remote terminals because of the line impedance which is effective in reducing the severity of the fault.

C. Single-line-to-ground faults are the least severe to the system and the margin for transient stability is greater than that for a three-phase fault at the same location. Where long lines are involved, it may be possible to transfer more power across the system with a single-line-to-ground fault near the center of one of the lines with both lines in service, than can be transferred with the faulted line removed from service. In this case, the system stability is not in jeopardy thus relaying times are not a critical factor. On short lines, fault severity is nearly independent of fault location. Therefore constant relaying time will be required for single-line-to-ground faults anywhere on the line, but this relaying time is not nearly as critical as for three-phase faults.

D. Faults on a short line in parallel with a weak interconnection result in a significant decrease in the ability to transfer power when the faulted line is removed from service. For this reason, the stability margin will in general be small so that is it is imperative to quickly initiate clearing of the fault. Here too, three-phase faults will be the most severe.

The points noted apply specifically to the system shown in Figure 1. In general, similar conclusions can be drawn with respect to any system. The intent here has been to show how such studies can be used to establish the requirements of a relaying scheme that will meet the needs of the system. It may be unrealistic to establish a maximum relaying time that is intended to apply for all fault types and all fault locations. A single specified time may tend to be unduly long for severe faults wherein system stability might be jeopardized, and/or it may be too short for light faults so as to encourage some reduction in the security margins in order to meet the specifications.

TRANSIENT PHENOMENA AND RELAY DESIGN CONSIDERATIONS

Electromechanical Relays

In general, experience has indicated that a knowledge of the steady state response of the power system and of the steady state response of the relay provided adequate information for the design and application of electromechanical type distance relays. Two exceptions can be noted.

1. An electromechanical relay may be affected by the dc component of current associated with a range of fault incident angles for lines having high impedance angles. The tendency of this response is to cause the relay to overreach. It is possible through proper design

to minimize the overreach. This has been done where minimum overreach is considered a necessity, such as in first zone distance units.

2. In many distance relays, a bolted fault just in front of the relay will cause the polarizing voltage to disappear and render the relay inoperative. To overcome this situation, these relays are provided with a memory circuit in the polarizing circuit of the relay. The memory circuit provides sufficient voltage for a short time after the fault for the relay to respond on a dynamic basis.

Although it was generally appreciated that other power system and instrument transformer transients existed, electromechanical type relays provided satisfactory performance in the presence of these transients without the need for special design or application consideration. The response of the electromechanical relays to these transients is minimized because of the inertia of the device.

Static Relays

Static relays have no inherent inertia, but it is possible by circuit design to include an effective inertia that can be used to control the transient response of the relays. Static relays can be made very fast by reducing the effective inertia, but the security will be poorer because the lower inertia increases the response to system transients. Security can be improved by increasing the effective inertia, but this inevitably leads to an increase in the average operating time. Because static technology makes it relatively easy to control the effective inertia, static relays can be designed to operate with an optimum balance of speed and security in the presence of the transients introduced by the power system.

System Transients

The following transients are generally those that should be considered, but the importance of each type will depend on the specific design and application of the relay in question.

A. DC offset in the current – This transient has long been a consideration in relay design and will be familiar to everyone.

B. DC offset in voltage – This transient results from the dc component of current in systems where the source impedance angle is different from the line impedance angle.

C. High frequency transients – These transients arise as a consequence of the line shunt capacitance, which will have a charge prior to the fault that can be significantly different from the charge during the fault. The transition results in high frequency transient currents and voltages which modify the current and voltage signals to the relays. The effect on the relays' ability to make the measurement is usually a function of the relative magnitude of the high frequency quantities with respect to the fundamental frequency quantities. The frequency of these transients is also a significant factor.

D. Capacitor voltage transformer transients – CVT's used for protective relaying usually consist of R, L and C circuits which introduce transients when there is a sudden change in the applied voltage. In general, the lower the capacitance of the coupling capacitor, and the more drastic the change in voltage as a result of the fault, the more significant will be the transient in terms of relay response.

E. Current transformer transients or errors – Current transformer transients or errors arise primarily as a result of CT core saturation. In general, the error between the primary and secondary currents has been more of a consideration of dependability rather than security in relay design. However, it cannot be disregarded in considerations of security.

F. Transients due to series capacitors – If series capacitors are used on the system, a low frequency transient may be introduced rather than the dc offset that is often introduced in uncompensated systems. This low frequency transient is usually more difficult to analyze than the dc offset in terms of the relay response.

When the protective gaps in the series capacitor flash, the usual inductance in series with the gap (to limit the discharge current) produces a high frequency voltage across the capacitor, giving rise to high frequency currents and voltages in nearby relays. Where distance relays are involved, the "negative" reactance of the series capacitors must also be considered.

STATIC RELAY CHARACTERISTICS

Figure 2 shows typical average time curves for distance and overcurrent functions. The following comments can be made about these characteristics.

1. Response Time, Overreaching Functions

Figure 2A shows typical average time characteristics of distance functions that may be applied as the overreaching tripping functions in a pilot relaying scheme. They are set to overreach the line so that they will be capable of detecting all faults on the line. The characteristic shown has an operating time that varies as a function of the fault location; i.e., the operating time increases as the fault approaches the relay balance point. The band in the operating time (cross-hatched area) comes about because of the source impedance behind the relay; i.e., the operating time for remote faults will increases somewhat as the source impedance is increased. For faults near the relay location, the operating time is very fast and relatively independent of source impedance (assuming source impedances of reasonable values). As the source impedance gets very large, the relays will take longer to operate or will not operate at all. The variable characteristics have been optimized to provide speed and security in the presence of the transients discussed previously. Speed is obtained for close-in faults where relay signal levels are strong and tend to swamp out any transient effects. On the other hand, security is enhanced for faults near the balance point where the signal levels are low relative to the transients, and the extra operating time allows time for the transients to diminish before an output is produced. The latter feature is extremely important in first zone functions.

2. Settings, Overreaching Functions

It is common practice in setting the overreaching trip functions to minimize the reach on long lines to avoid possible interference from load flow. On the other hand, the effect of load flow is insignificant relative to the relay setting on short lines so that the reach can be increased relative to the line length.

Figure 2A demonstrates the effect of the different relative reach settings. On long lines, the operating times will be somewhat greater for line end faults because of the reduced reach. However, the operating time will be relatively constant on short lines because of the increased reach settings. Thus on short lines where fault severity is relatively independent of fault location, fast operation will be obtained for faults anywhere on the line.

3. Response Time, First Zone Functions

Figure 2B illustrates typical characteristics for first zone distance functions. Here again, a variable characteristic is demonstrated. The important thing to note is that the variable characteristic produces very fast operating times for close-in faults where speed is of major importance. Operating times will be somewhat longer for faults near the balance point, but security will be enhanced because the tendency to overreach will be minimized.

4. Response Time, Overcurrent Functions

Typical overcurrent characteristics are shown in Figure 2C. Here too, a variable characteristic is shown. The variable characteristic will provide fast operation at high multiples of pickup current and will become somewhat slower as the operating current approaches the pickup value. The response of the variable overcurrent function can be compared to the response of the variable distance function in that the overcurrent function will increase in speed for faults closer to the relay location similar to the way the distance relay performs.

5. Other Advantages of the Variable Characteristic

In blocking type schemes to be discussed subsequently, coordination must be achieved between the blocking function at one end of the line and the tripping function at the other end. Coordination will be facilitated if the blocking function can be made to operate as fast as or faster than the tripping function. The variable characteristic provides this feature; i.e., faults for which coordination is expected will be closer to the blocking function than to the remote tripping function, hence the blocking function will tend to operate as fast as, and generally much faster than the tripping function. Since the tripping functions are directional by design they must not operate for faults behind the relay (reverse faults). The variable characteristic with its controlled inertia will provide added security during reverse faults. This is so because the inertia will be quite effective at the inception of the fault when the transients (particularly CVT transients) will in general be greatest.

6. Other Refinements and Features

The shape of the characteristic of distance functions in General Electric static relays is determined by the pickup setting of a static timer. This timer in effect measures the phase angle between two voltage quantities that are derived from the system voltage and current. The characteristic (see Figure 3) can be shaped into a circle (4.167 ms), a lens (>4.167 ms) or it can be made tomato shaped (<4.167 ms), where the time in the parentheses indicates the steady state pickup setting of the timer. The circular, or mho, characteristic is the most common of the three and will be found in the majority of applications. The lens-shaped characteristic would most likely be used in long line applications, whereas a combination of lens and tomato might be found in an out-of- step tripping scheme. The ease with which the shape of the characteristic can be changed makes the static mho distance relay well suited to meet the requirements of a variety of applications.

Relay characteristics are generally plotted on an R—X diagram in terms of their steady state response, hence the pickup time spoken of in the preceding paragraph is given in terms of the steady state response. The characteristic timer used in the tripping functions in the latest line of static relays have been further refined to have a transient as well as steady state pickup time. For this reason, the pickup time is given in terms of two values as shown in Figure 3. The transient pickup time "a" refers to the minimum duration of the first input block that is required to operate the timer. The timer will then maintain an output if the succeeding blocks are then greater than or equal to the stady state pickup "b" and are less than 5 milliseconds apart. If the first input block is less than the transient pickup time, the timer will produce an output if the succeeding blocks are at least equal to the steady state pickup and are less than 5 milliseconds apart.

Static timers in general are designed so that removal of the input signal will cause the input circuit to reset immediately, thus making it necessary to begin the count at zero when the next input is applied. In integrating timers, used in the characteristics shown in Figure 3, the input circuit does not reset immediately after removal of the input. A certain amount of time is required before the input circuit resets completely. Thus, if the next signal is applied before the reset is completed, the timer does not have to start the count from zero. The overall effect is to speed up the operation of the distance function. The integrating timer has been designed to provide faster operation for internal faults where studies have shown that the first series of input blocks can be spaced very close together. The trip function timers have been designed with a transient pickup to prevent any outputs during close-in reverse faults where the system transients might be sufficient to cause the first input block to approach the steady state pickup of the timer.

Specific details have not been presented in this section on either the design or operation of the described functions. An attempt has been made here to show that static relays must be capable of operating in a transient as well as a steady state environment. Significant steps have been taken in the design of static relays to provide functions that will perform with an optimum balance of speed and security in this type of environment.

SCHEME TYPES, OVERALL PERFORMANCE AND SCHEME SELECTION

The overall relaying time for any given scheme will be dependent on the type of scheme, the channel response time and the operating time of the fault detecting relays. The exact influence of each of these factors will become evident as the various types of schemes are examined.

Three basic schemes will be discussed - blocking, tripping and a hybrid scheme which combines some of the features of both. Unblocking schemes are often placed in a fourth category, but these schemes are implemented via changes in the channel receiver logic and are simply a variation of a tripping type scheme.

Blocking Scheme

A blocking scheme includes both tripping and blocking functions at all terminals of the line. Figure 4 illustrates simplified logic for this type of scheme. Operation of any one of the blocking functions will initiate a blocking signal to block tripping at all terminals of the protected line. The tripping functions at each terminal are permitted to initiate a trip within a fixed time delay after they operate if no blocking signal is present. Tripping will be permitted at each terminal independent of the trip function operation at the remaining terminals. The fixed coordinating time delay allows time for a blocking signal to be received from the remote terminals. Its duration is dependent on the operating time of the blocking functions, the channel response time and the signal propagation time. It also includes a suitable margin for security. Hence, trip time at any terminal is independent of the operation of the trip functions at the remote terminals and is equal to the operating time of the local tripping function plus the fixed coordinating time delay.

Figure 5A illustrates the total relaying time for a blocking scheme using distance relays having the variable characteristic shown in Figure 2A. A long line is assumed with a strong source (small impedance) at the left end, and a weak source (large impedance) at the right end. A high speed channel is assumed an the reach of the tripping functions is minimized so that there will be no interference from load flow. The overall relaying time at each terminal is independent of the operation of the trip functions at the remote terminals, and it is simply equal to the operating time of the trip function plus the coordinating time delay. Figure 5B illustrates the effects of using a medium speed channel. In this case, the relaying time at each terminal is increased by an amount equal to the increase in channel time.

Figures 6A and 6B illustrate the effects of adding first zone functions to the scheme. The cross-hatched area illustrates the time saved at the left terminal. These functions have minimal effect on the overall relaying time for the scheme using a fast channel, but do offer considerable improvement where a medium or slow speed channel is used.

The important thing to note in figures 5 and 6 is that high speed tripping will always be initiated at the terminal nearest the fault; i.e., for close-in faults where high speed tripping is required. Tripping at the remote terminal will be somewhat slower, but the added delay can be tolerated from a stability standpoint as demonstrated in an earlier section of this paper.

Figures 7A and 7B illustrate the overall relaying time for a blocking scheme applied to a short line. In this case, the tripping functions can be set to reach well beyond the remote terminal so that the relay response will be nearly constant over the entire length of the line. The only delay that will be added is that due to the coordinating time. The addition of a first zone function, shown in Figure 7B, will be more effective where medium to slow speed channels are involved. The cross-hatched area illustrates the time savings to be made by the addition of first zone functions at the left terminal.

Tripping Scheme

A tripping scheme includes only tripping functions at each terminal. These functions key their associated transmitter to the trip frequency when they operate and initiate tripping only if a trip signal is simultaneously received from the remote terminals. See Figure 8 for simplified logic. Therefore, a tripping scheme can be defined as one which requires operation of the local trip function and receipt of a trip signal from the remote terminals before tripping will be initiated. Thus the tripping functions at all terminals must operate before tripping can be initiated at any terminal.

Figure 9A shows the overall operating time for a tripping scheme applied to a long line with a weak source at the right end and a strong source at the left end. A medium speed channel is assumed. In this type of scheme, tripping cannot be initiated at any terminal until a trip signal is received from the remote terminals. Thus, for a fault at the left end of the line shown in Figure 9A, the trip function there may operate quickly, but tripping will not be initiated until the trip function at the right terminal operates to send a trip signal. Figure 9B illustrates the effects of adding first zone functions to the tripping scheme. Here the functions are quite effective and offer a significant improvement to the overall relaying time. Note that the relays can be set to reach well beyond the remote terminals on short line applications so that the relay response will be very flat. Thus, on short lines, the tripping time at each terminal will essentially be equal to the operating time of the trip relay plus the channel time.

Hybrid Scheme

The hybrid scheme utilizes both blocking and tripping functions. In this scheme, the channel is normally operated in a blocking state, but operation of the trip functions will key it to the trip state. Receipt of the trip frequency and operation of the trip function will initiate a trip output, hence the scheme basically operates similar to the tripping scheme. See Figure 10 for simplified logic. However, in a true tripping scheme, only the operation of the trip function can key the transmitter to the trip frequency. In the hybrid scheme, the transmitter can also be keyed to the trip frequency whenever the trip frequency is being received from a remote terminal and the local blocking function has not operated. This in effect repeats the trip signal back to the remote terminal so tripping can be initiated there. In essence then, the scheme operates like a blocking type scheme through the inclusion of the repeat feature. This repeat feature is generally provided at those terminals where weak infeed conditions result in the tripping functions operating very slow or not operating at ail. Tripping time at the heavy infeed terminals (where the trip functions operate very fast) will then be equal to the trip function operate time plus twice the channel time (signal repeated).

The overall operating time for a hybrid type scheme is illustrated in Figure 11 for a long line application with a strong source at the left end and a weak source at the right end. In this type of scheme blocking functions are added at each terminal so that a trip signal will be sent to the remote terminals whenever a trip signal is received and the blocking functions have not operated (operation of the trip functions will also key the transmitter to the trip frequency). Without the blocking functions and the added keying logic, the scheme is simply a tripping scheme and the operating times shown in Figure 9 would be applicable. The effect of the signal repeat circuitry is to cause faster tripping at the terminals that would ordinarily be slowest in a true tripping scheme. This effect is illustrated by the cross-hatched area in Figure 11A where the overall tripping time at the left terminal has been reduced by that amount. Basically, for a fault near the left terminal, the tripping function there will operate very fast. When it operates, it sends a trip signal to the remote terminal which is repeated on back because the blocking unit at the right terminal will not operate for this fault. This turn around, or repeat, occurs before the tripping function at the right terminal operates for the remote fault, so that the trip signal will be sent to the left terminal more quickly thus hastening tripping at the left terminal. A medium speed channel was assumed for this example. If a faster channel were used, the effect at the left terminal would be more dramatic. Tripping at the right terminal can also be decreased significantly by adding weak infeed trip circuitry. This circuitry basically permits tripping to occur at the weak infeed terminal whenever a trip signal has been received there and a blocking function has not operated. Other supervisory functions, either sensitive overcurrent or undervoltage are included as part of the weak infeed trip circuitry to insure the necessary security.

Direct Transferred Tripping
Not shown in the diagrams is the effect of using direct transferred tripping equipment. With this type of equipment, dual channels are generally used so that the receipt of a trip signal by both receivers is required to initiate a trip. If this equipment is already installed to provide protection for equipment failure (shunt reactors, etc.) it can be keyed whenever a trip signal is produced by the line relays. Trip initiate time at all terminals (other than the fastest one to initiate a trip) will then be equal to the trip initiate time of the fastest terminal plus the transferred trip channel time. For example, assume a fault at the left end of the line protected by the scheme shown in Figure 9B. If direct transferred tripping equipment were available, and if it were keyed whenever the first zone function initiated a trip, then tripping at the right terminal would occur at X plus the transferred trip channel time instead of the Y time shown. This of course assumes that the channel time is less than Y - X milliseconds, a not too unreasonable assumption if a fast channel is used.

SCHEME AND CHANNEL SELECTION

The above discussion examined the various schemes from a standpoint of overall operating time. The choice of scheme to be used and the functions used to implement the scheme along with the choice of communications channel involve other considerations.

Relaying Channels
Basically two types of channels, ON-OFF or frequency shift, are used with pilot relaying schemes.

In the ON-OFF type of channel, no signal is sent until the transmitter is keyed to begin a signal transmission. ON-OFF type channels are applied quite extensively in blocking relaying schemes. In such schemes, the channel is called upon to operate and send a blocking signal only during external faults within the reach of the blocking detectors employed in the scheme. If the channel is inoperative, no blocking signal can be sent. Hence overtripping can result if the channel is out of service when an external fault occurs. Since the channel is normally operated in the OFF state, malfunctions cannot be detected until the channel is called upon to operate. Therefore, channel status indication is not available for continuous use in the relaying scheme logic. Check-back schemes are available wherein the channel can be periodically checked on an automatic or manual basis.

In a frequency shift type of channel, a signal is sent continuously at one frequency until the transmitter is keyed at which time it will shift to another frequency. Frequency shift channels are used extensively in tripping type schemes. The continuous frequency is commonly referred to as the "GUARD" frequency. The transmitter will be keyed to the "TRIP" frequency for faults within the reach of the tripping detectors employed in the scheme. Since a signal is always being sent, the channel can be monitored on a continuous basis and channel status can be used continuously as part of the overall relaying logic. The scheme is usually arranged so that an extended loss of channel will result in all tripping by the pilot relaying scheme being blocked.

Frequency shift channels may also be used in blocking type relaying schemes and are almost always used in unblocking type relaying schemes. In a blocking scheme, the channel is continuously keyed to the "TRIP" frequency and it is shifted away from the "TRIP" frequency to block tripping. An unblocking relaying scheme is basically the same as a tripping scheme except for some changes in the channel logic. Unblocking type channels are applied when the carrier is to be coupled directly to the power line. The receiver includes logic to recognize that the signal might be lost as the result of attenuation during an internal fault. This logic, commonly referred to as "U" or "UNBLOCKING" logic, permits a trip output for a short period of time after a loss of signal has occurred. If the signal loss has occurred as a result of an internal fault, the appropriate trip detectors will have operated and tripping will be initiated. On the other hand, if the signal loss has occurred for other reasons, the trip detectors will not have operated and tripping will not be initiated during the short period of time that the receiver is producing a trip output. Unblocking logic should also be included with the receiver when a frequency shift channel is applied on the power line with a blocking or hybrid scheme.

Blocking Scheme

Historically, blocking schemes have been implemented via ON-OFF type communications channels. The channel is called on to operate only during external faults within reach of the blocking functions. Channel information is not required during internal faults. For this reason, loss of the channel will not affect tripping for internal faults, but overtripping will result if the channel is inoperative and an external fault occurs within the reach of the tripping functions. A blocking type scheme will permit tripping to be initiated at all strong infeed terminals in the event a weak infeed condition existed at one or more of the remaining terminals. The weak infeed terminals will likely be tripped sequentially on redistribution of the fault current after the fault is cleared at the other terminals, or some form of transferred tripping can be used to remove the fault. The blocking scheme can therefore be considered very dependable but less secure. When using a frequency shift type channel to implement a blocking scheme, the scheme is usually designed so that all tripping will be blocked whenever the channel is lost. This then reduces the dependability of the scheme but does add to the security.

Tripping and Hybrid Scheme

Tripping schemes in general use frequency shift type channels. Receipt of a trip signal is required along with the operation of a trip function before tripping will be initiated. The scheme is arranged so that loss of the channel will block tripping for any condition until the channel is restored to service. Tripping will be blocked at all terminals whenever weak infeed conditions exist at one of the terminals. A signal repeat feature can be provided by adding a blocking function and some minor logic at a weak infeed terminal so that tripping will be permitted at the remaining terminals. This, in effect, converts the scheme into a hybrid scheme. The scheme then essentially operates similar to a blocking scheme in that tripping will be permitted at the strong infeed terminals during weak infeed conditions. Some minor logic and supervisory functions can also be included to implement weak infeed tripping. Thus, the tripping type or hybrid type scheme will be very secure in that overtripping cannot occur as a result of the channel being inoperative because it will lock out and prevent tripping whenever it is out of commission. On the other hand, they can be considered somewhat less dependable for the very same reason.

One Versus Two Primary Relaying Schemes

On less important lines where it is common practice to use a single high speed relaying scheme, it may be desirable to consider a blocking scheme over an ON-OFF type channel. This would be especially desirable if the possibility of overtripping as a consequence of channel failure could be tolerated. In this way, the protection would be very dependable in that tripping would be assured for all internal faults. The scheme would be lacking somewhat in security, but an external fault must occur within the reach of the tripping functions while the channel is out of service before overtripping could occur.

On important lines, where it is becoming common practice to provide two high speed relaying schemes, it may be desirable to consider using schemes with a channel that blocks all tripping on channel failure. In this way, loss of the channel associated with one of the schemes would lock out tripping by that scheme thus preventing the possibility of overtripping. Since different routes would most likely be used for each channel, and since it is unlikely that both channels would be lost simultaneously, the second scheme would provide redundancy and so in effect provide dependability. Thus, both dependability and security would be provided.

Effects of Infeed

In many applications the line will have substantial fault current infeed from all terminals, and the load impedance will appear to be large relative to the line impedance. Thus, the overreaching functions can be set long relative to the line length to assure fast operation for faults anywhere on the line. For these applications, the type of scheme chosen is not critical with respect to speed since either a blocking or tripping scheme will offer comparable performance. A hybrid scheme would offer no specific advantages because of the sufficient infeed conditions. Here, the major application consideration is the degree of dependability and security required as described above.

Direct Tripping Functions

The relaying channel should be selected with a response time that is compatible with the speed and security needs of the relaying scheme and the system. Occasionally, limited frequency spectrum will result in channel bandwidth restrictions and consequently long channel times. Where this is the case, direct tripping functions can be used to provide high speed tripping for severe faults as previously noted. Direct tripping functions would also be beneficial in tripping type schemes applied on long lines.

Ground Fault Resistance

Finally, another factor that is assuming increasing importance in the selection of the type of relaying scheme is the consideration of high resistance ground faults. On lines with ground wires, high resistance ground faults are not a frequent occurrence, but can occur due to faults involving trees, brush fires under the lines, etc. Because of the restricted sensitivity of distance relays to faults involving high fault resistance, it is common practice to resort to directional overcurrent fault detectors to detect these types of faults. However, because these directional overcurrent fault detectors are more sensitive than distance type relays, they tend to "reach" much farther beyond the protected line section. Therefore, some reduction in security results; especially for those applications operating with a channel that will permit tripping when the signal is lost. It is possible to minimize the exposure to operation during external faults by increasing the pickup setting of the overcurrent functions. The higher the setting, the less dependable the scheme will be on internal faults and the more secure on external faults - and vice versa. The setting of the overcurrent fault detectors is somewhat akin in this context to adjusting the reach on an overreaching distance function; i.e., the greater the overreach the faster the distance function will be for remote line end faults but the greater will be the probability of operating on external faults.

In applying these directional overcurrent functions, the setting to be made will be dependent on the type of scheme that is selected. In a blocking scheme, both blocking and tripping functions must be provided. The tripping function must be set somewhat higher (less sensitive) than the remote blocking function to assure proper coordination during external faults. A tripping scheme utilizes only tripping functions, therefore there is no coordination requirement, and they can be set more sensitively than their counterparts in a blocking type scheme. Offhand, it would appear that a tripping scheme would therefore offer more sensitive protection for high resistance ground faults than a blocking type scheme. However, this may not be true and each application should be examined on an individual basis.

Consider a long line with a high resistance ground fault at one end. For this situation, there will generally be much more infeed from the end nearest the fault than from the remote end. If the infeed from the remote end is insufficient to operate the tripping function at that terminal then tripping would be blocked at all terminals if a tripping type of scheme were used. On the other hand, the infeed from the end nearest the fault will be much greater than the infeed from the remote end. If a blocking type of scheme were used, the probability exists that the tripping function there would operate because of the difference in infeed even though it would be set less sensitively than the same function in a tripping type of scheme. Thus tripping would be initiated at the near end terminal with a blocking scheme. The remote end would likely trip sequentially as a result of the redistribution of fault current or it can be transferred tripped when the near end relays operate.

Now consider a middle of the line fault where the infeed at both terminals is insufficient to operate the tripping functions in a blocking type of scheme, but sufficient to operate the more sensitively set functions in a tripping type of scheme. For this fault, the tripping scheme would offer more sensitive protection. Therefore, on those applications where high resistance ground faults are of concern, and where two high speed relaying schemes are to be used, it may be desirable to consider operating one of the schemes in a blocking mode and the other scheme in a tripping mode. In this way, the sensitivity to high resistance ground faults can be optimized.

SUMMATION

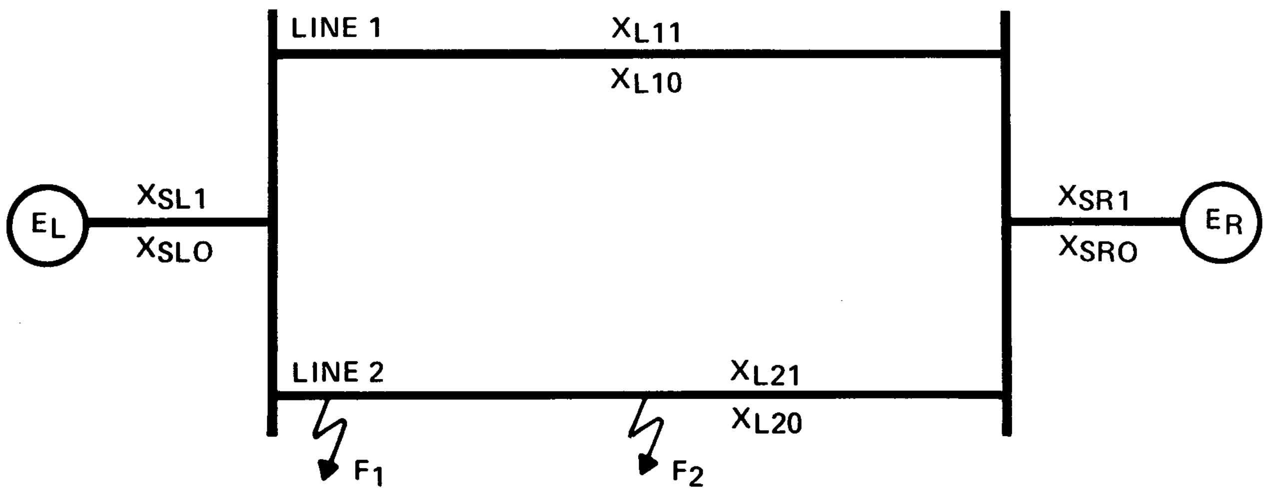
A general discussion of the considerations involved in implementing a high speed pilot relaying scheme has been presented. It was not the intent here to present the detailed technical aspects of the I relays and schemes, but rather to discuss them in general and to point out the possible advantages and disadvantages of each.

The power system was looked at from a standpoint of stability to demonstrate the importance that fault severity plays in specifying relay operating times. Typical relay characteristics were illustrated and the role that they play in determining the overall operating time of various type schemes was shown. A qualitative rather than quantitative analysis was used to point out the advantages of the variable type characteristic illustrated in Figure 2. The variable type characteristic is used in General Electric's latest relay designs because it offers superior performance in terms of both speed and security. The performance of these variable characteristics has been proven on the Model Power System where it is possible to duplicate the transient conditions encountered in actual service.

The advantages and disadvantages of the various type schemes were pointed out and the role that the channel plays was also noted. Schemes that operate with a channel that locks out all tripping when the channel is inoperative will offer the most in terms of security, but the least in terms of dependability. On the other hand, schemes that permit tripping when the channel is inoperative will offer the most in terms of dependability, but the least in terms of security. Each application should be studied in terms of the needs of the system before a scheme is selected.

The discussion was presented predominantly in terms of distance type relays and schemes utilizing distance type relays. However, it was pointed out that the operation of the variable type overcurrent characteristic is similar in performance to the variable type distance characteristic. In that context, similar philosophies can be applied to the application of either type. Phase comparison type relaying was not discussed, but it should be realized that overcurrent fault detectors are used in this type of scheme to initiate the comparing process. To that extent at least, similar arguments to that noted throughout this paper will also apply to a phase comparison type scheme.

Series compensated line protection was not discussed specifically, but relays and schemes have been developed and are in use on series compensated lines. The same basic philosophies discussed above apply with regard to both relay and scheme design. The performance of the relays in the presence of the transients introduced by the series capacitors may be somewhat different from that on an uncompensated line. A discussion of these differences is beyond the scope of this paper, but simulator studies and in-service experience has indicated the soundness of the design philosophy for application on series compensated lines.



$$P = \frac{E_L \, E_R \, \mathrm{Sin}\delta}{X_T}$$

FIGURE 1

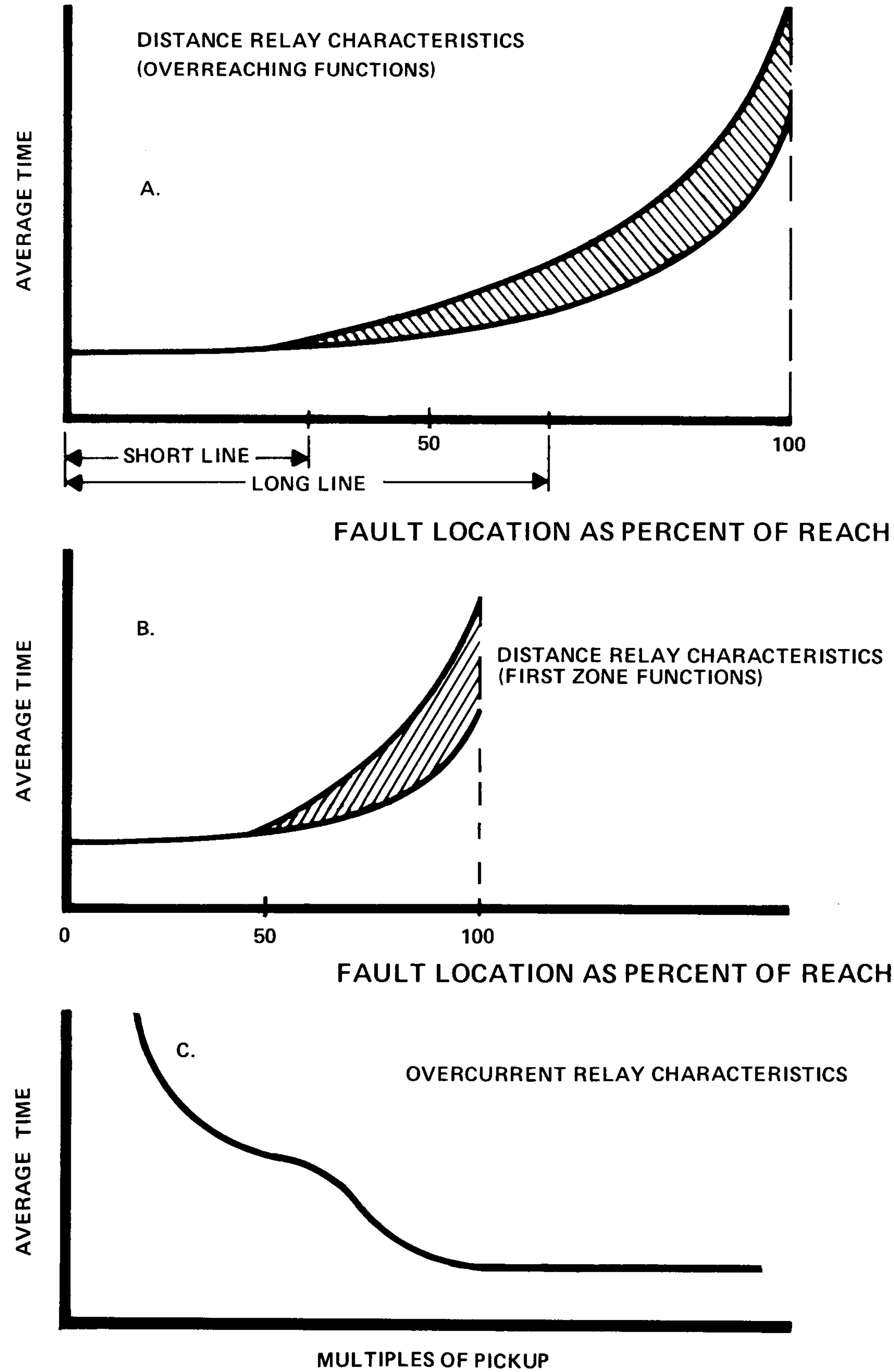
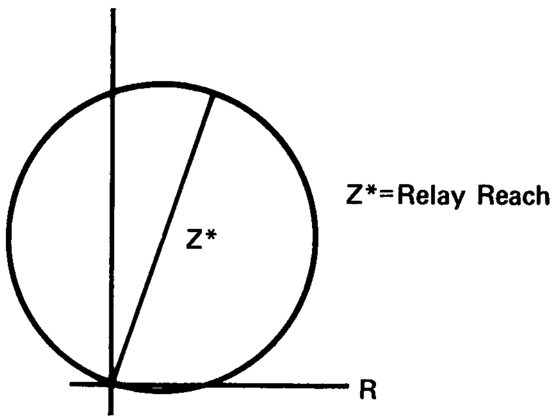
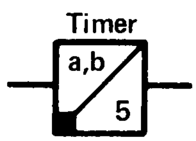

AVERAGE TIME
DISTANCE RELAY CHARACTERISTICS
(OVERREACHING FUNCTIONS)
A.
SHORT LINE
LONG LINE
50
100
FAULT LOCATION AS PERCENT OF REACH
AVERAGE TIME
B.
DISTANCE RELAY CHARACTERISTICS
(FIRST ZONE FUNCTIONS)
0
50
100
FAULT LOCATION AS PERCENT OF REACH
AVERAGE TIME
C.
OVERCURRENT RELAY CHARACTERISTICS
MULTIPLES OF PICKUP

FIGURE 2



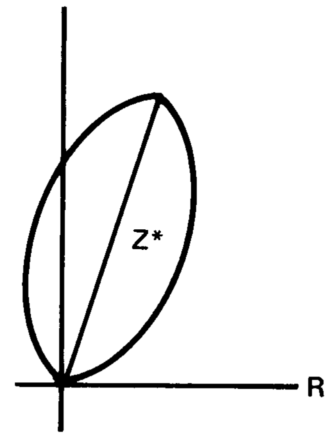
A. CIRCLE (MHO)



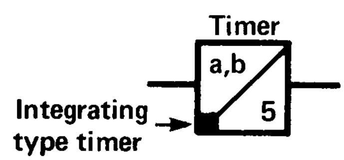
a = Transient Pickup,>b

b = Steady State Pickup = 4.167 ms

5 = Dropout time



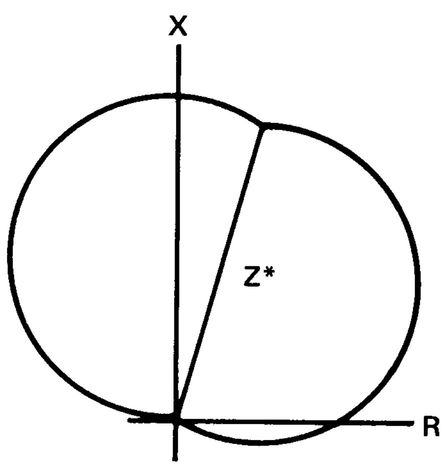
B. LENS



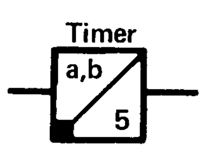
a = Transient Pickup,>b

b = Steady State Pickup,>4.167 ms

5 = Dropout time



C. TOMATO



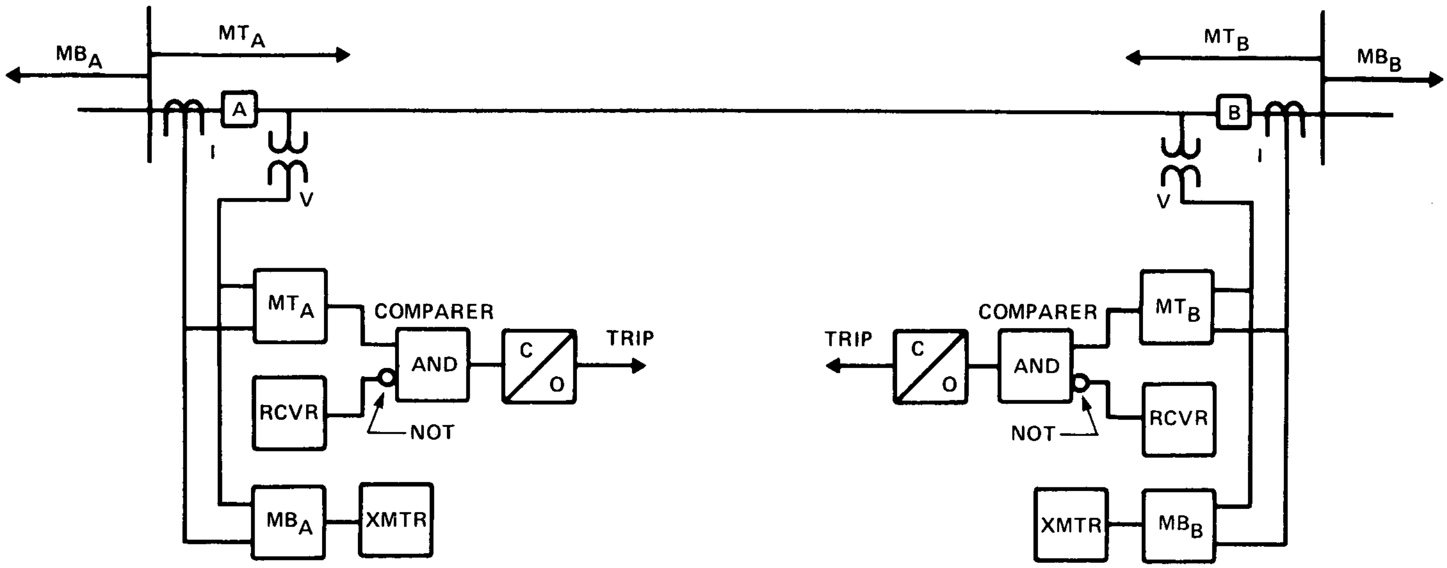
a = Transient Pickup,>b

b = Steady State Pickup,<4.167 ms

5 = Dropout time

FIGURE 3

STATIC DISTANCE RELAY CHARACTERISTICS

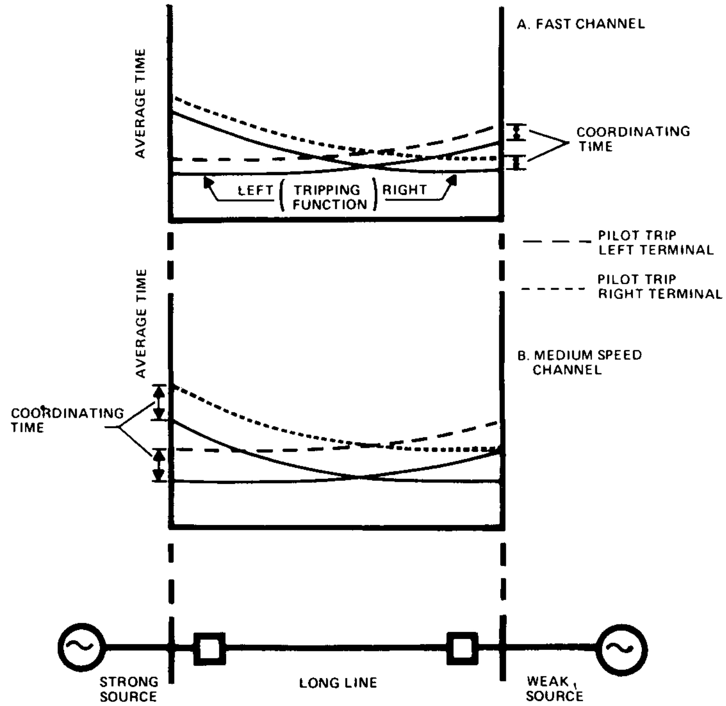


NOTES:

1. MT – Overreaching Trip Function
2. MB – Blocking Function
3. Operation of Blocking Function Keys XMTR to Blocking Frequency
4. Receipt of Blocking Signal Blocks Tripping at Comparer
5. C = Coordinating Time Delay
6. Operation of Trip Function <u>and</u> No Blocking Signal From RCVR Initiates Trip After C Time Delay

FIGURE 4

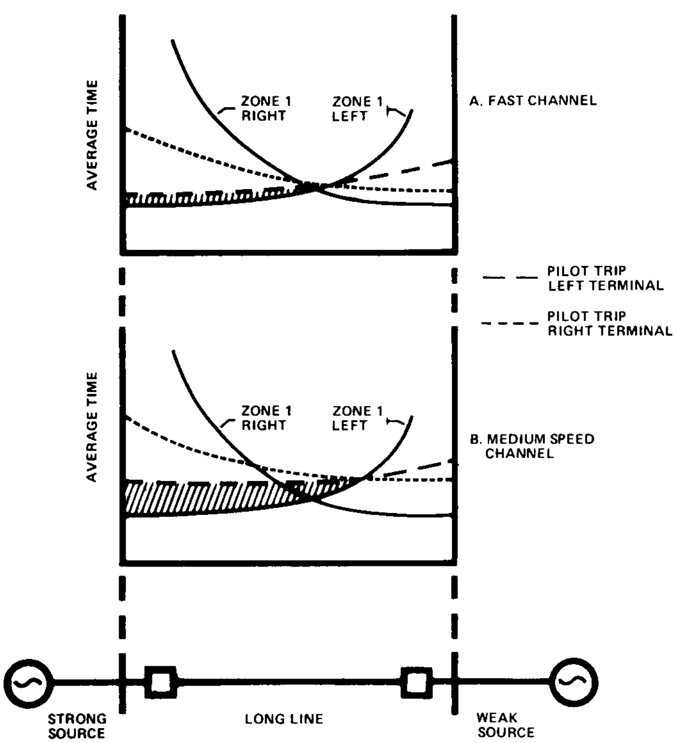
SIMPLIFIED LOGIC FOR BLOCKING SCHEME



BLOCKING TYPE SCHEME

TRIPPING TIME VERSUS FAULT LOCATION

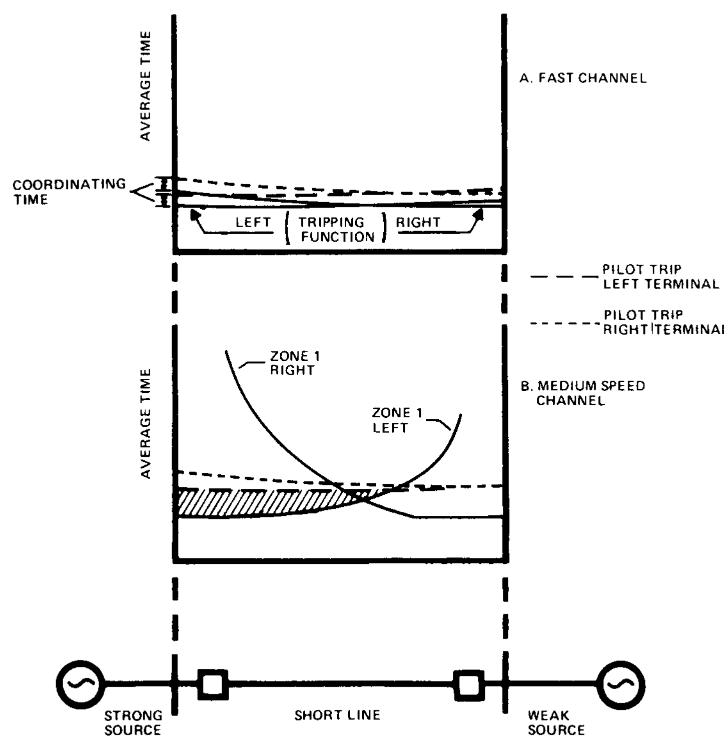
FIGURE 5



BLOCKING TYPE SCHEME

TRIPPING TIME VERSUS FAULT LOCATION

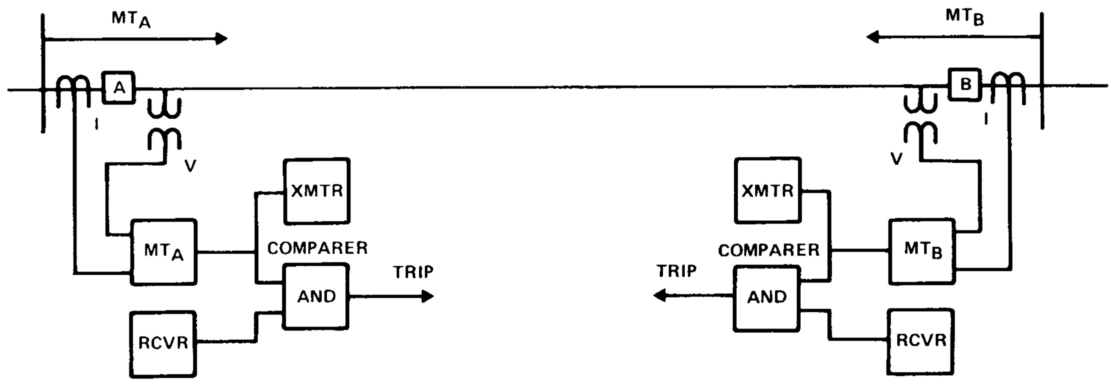
FIGURE 6



BLOCKING TYPE SCHEME

TRIPPING TIME VERSUS FAULT LOCATION

FIGURE 7



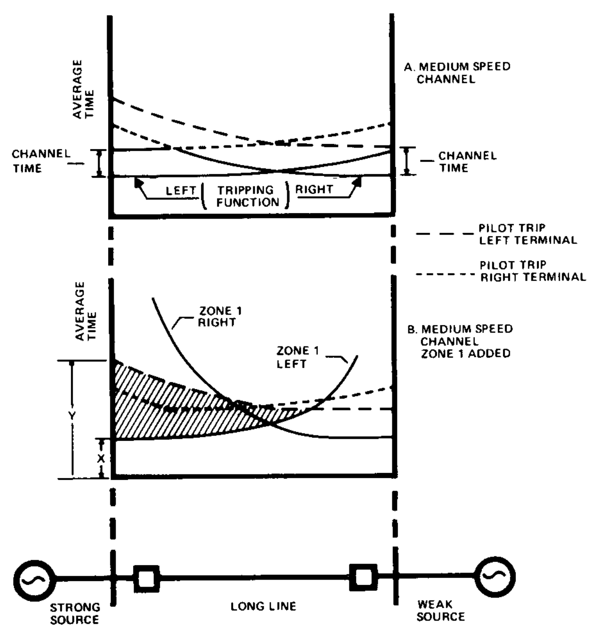
NOTES: 1. MT – Overreaching Trip Function

2. Operation of Trip Function Keys XMTR to Trip Frequency

3. Operation of Trip Function and Receipt of Trip Frequency Initiates Tripping

SIMPLIFIED LOGIC FOR TRIPPING SCHEME

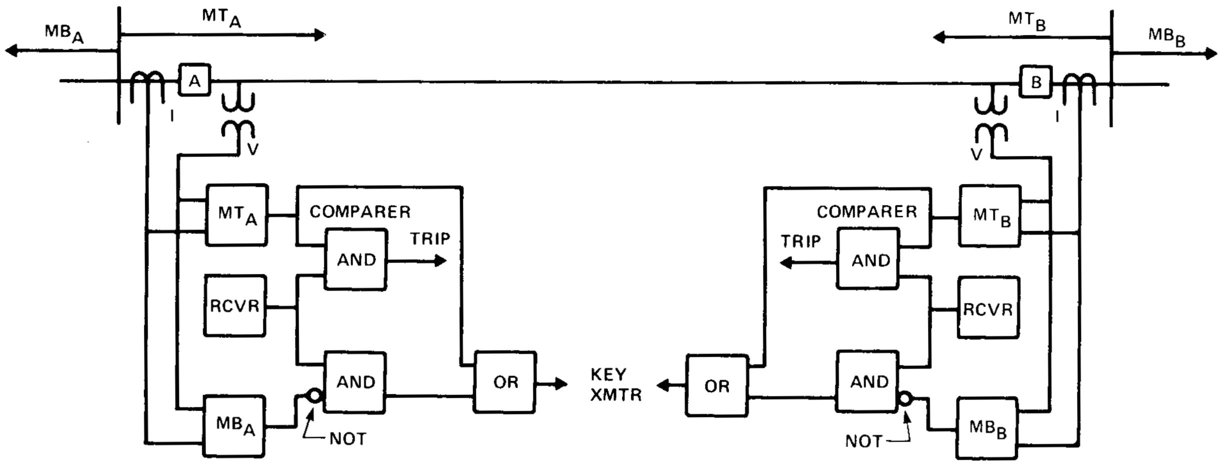
FIGURE 8



TRIPPING TYPE SCHEME

TRIPPING TIME VERSUS FAULT LOCATION

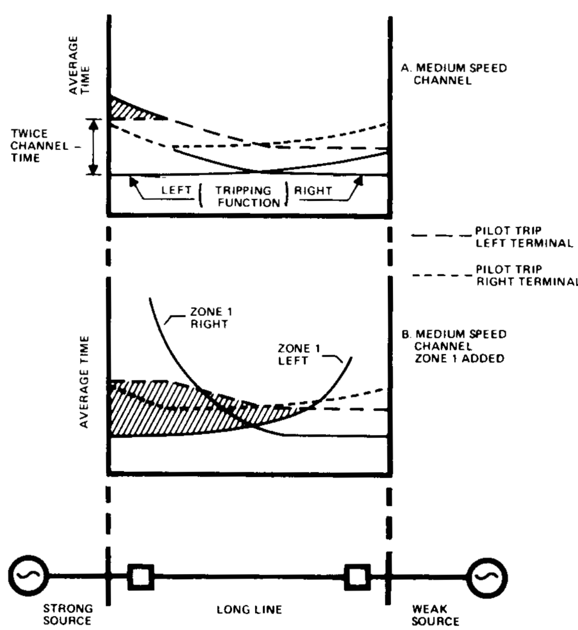
FIGURE 9



NOTES:
1. MT – Overreaching Trip Function
2. MB – Blocking Function
3. Operation of Trip Function Keys XMTR to Trip Frequency
4. Receipt of Trip Frequency and No Blocking Function Output Keys XMTR to Trip Frequency (at Weak Infeed Terminal)
5. Operation of Trip Function and Receipt of Trip Frequency Initiates Tripping

SIMPLIFIED LOGIC FOR HYBRID SCHEME

FIGURE 10



HYBRID TYPE SCHEME

TRIPPING TIME VERSUS FAULT LOCATION

FIGURE 11

APPENDIX I

Illustrated in Figure I-A is a simplified system that will be studied to demonstrate how the effect of system parameters should be considered in specifying the speed required from a high speed pilot relaying scheme.

System Stability and Power Transfer Reactance
For the system shown, it is possible to calculate the relative power flow across the system for various system parameters, fault types and fault locations via the familiar power transfer equation:

$$P = \frac{E_L\, E_R\, \text{Sin}\delta}{XT} \qquad (1)$$

where,

P = power transferred across the system
E_L = equivalent system voltage at the left end of the system
E_R = equivalent system voltage at the right end of the system
X_T = equivalent system reactance between the two sources E_L and E_R
δ = the angle between the two sources

It is assumed in equation (1) that all resistances are negligible and that all impedances are represented by their reactive component only. A plot of equation (1) yields the familiar power transfer curve shown in Figure I-B. From this figure it can be seen that maximum power transfer will occur when the angle δ equals ninety degrees. The actual magnitude of the maximum power will be dependent on the magnitude of the source voltages and the magnitude of the equivalent reactance X_T appearing between the sources. A method for calculating the equivalent reactance for a single-line-to-ground fault at F_1 in Figure I-A is demonstrated in Appendix I I. A similar type analysis can be used for other fault types.

It is possible to demonstrate via the power transfer curve the relative ability of the system shown in Figure I-A to remain transiently stable for a given set of system parameters, and for any given fault type and location. To do this, it is necessary to know the equivalent transfer reactance for each condition. A number of conditions were considered for the system shown in Figure I-A . The equivalent reactances for each of these conditions are listed in Table I along with the system parameters that were used in each case. From this table it can be seen that the equivalent reactance becomes smaller in magnitude for fault types in the following order.

1. Three phase — highest X_T
2. phase-to-phase-to-ground
3. phase-to-phase
4. single-line-to-ground — lowest X_T

Thus, the relative ability of the system to transfer power during a fault increases in the same order; i.e., greatest amount of power can be transferred for the lowest X_T whereas the least amount can be transferred for the greatest X_T. Hence a three phase fault at a given location will always present the most onerous condition to the system whereas a single-line-to-ground fault will always present the least onerous condition. The relative severity of a single-line-to-ground fault and of a phase-to-phase-to-ground fault will be dependent on the ratio of the system zero sequence impedance to the system positive sequence impedance (both as viewed from the fault). Lower ratios will lead to increased severity. In the limit, a single-line-to-ground fault will approach a phase-to-phase fault and a phase-to-phase-to-ground fault will approach a three phase fault as the ratio approaches zero. Thus, faults of this type will be more severe to the system when they occur near a generating station because of the relatively low ratio that can exist there.

It is now necessary to refer to the power transfer curve to demonstrate the relative ability of the system to maintain transient stability during a given disturbance. Three systems will be studied. The system configuration is shown in Figure I-A and the parameters for each are listed in Table 1.

1. Long Lines, Strong Sources

Consider the case of a three phase fault at F_1 in Figure 1-A. For this case, the equivalent reactance during the fault equals infinity (see case 1, Table 1). Thus, from equation (1), zero power can be transferred across the system with the fault on. Figure I-C shows the power transfer curves for the system with both lines in, with the fault on, and with the faulted line removed from service. These curves were drawn under the assumption that 1.0 per unit power equals the maximum power that can be transferred across the system with both lines in service and with 1.0 per unit voltage maintained at each source. It was further assumed that 0.4 per unit power was being transferred at the time of the disturbance, and that the mechanical power input to the system remained constant throughout the disturbance. The angle across the system prior to the disturbance is therefore approximately 23.6 degrees. When the fault occurs, power transfer will drop to zero and the machines will start to swing with respect to each other thus leading to an increase in the angle between them. It is assumed that the fault is cleared when the angle equals δ_2 degrees. At the instant the fault is cleared by removing the faulted line, the power transferred across the system will increase to that dictated by the power transfer curve with line 2 out. The system will be transiently stable when the area A_2 is greater than or equal to the area A_1. When A_2 is greater than A_1, the maximum angular swing between the two sources will be less than δ_4 degrees. When A_2 equals A_1 the system is at the transient stability limit and the angle δ_2 is referred to as the critical switching angle. If A_2 is less than A_1, the system is considered to be transiently unstable. For the example chosen here, the system appears to be quite stable. The angle $\delta_2 - \delta_1$ is assumed to be approximately 12 degrees for a three phase fault at F_1. This angle is considered typical for an EHV system with 2 cycle breakers and an assumed relaying time of one cycle. Also shown in Figure I-C is the power transfer curve with the three phase fault on, and with the breaker at the left end open. In this case the power transfer curve with the fault on and with the breaker near the fault open is not much less than the power transfer curve with the line removed from service. Thus, it is imperative that the breaker near the fault be tripped rather fast. If tripping at the right end then takes a little longer, the system will not be in jeopardy from the point of view of stability. Note that the angle $\delta_2 - \delta_1$ will increase for slower breaker and/or relaying times thus leading to an increase in area A_1 and a decrease in area A_2. Consequently, the stability margin will be reduced. Note that an increase in the initial power transferred will also lead to reduced stability margins.

Figures I-D, I-E and I-F illustrate a similar type analysis for a phase-to-phase-to-ground, phase-to phase and single-line-to-ground fault at the end of the line, respectively (see cases 2, 3 and 4 of Table 1). These figures show, as discussed previously, that the ability to transfer power increases as the severity of the fault is decreased because of the consequent decrease in the transfer reactance. It is of interest to note that the transfer reactance for the single-line-to-ground fault studied in case 4 of Table 1, and illustrated in Figure I-F is less than the transfer reactance for the system with one line out of service. This results in the ability to transfer more power with the single-line-to-ground fault on one line with both lines in service than with no fault and one line out of service.

Figure I-G illustrates the case for a single-line-to-ground fault in the middle of the line. In this case, the ability to transfer power and hence the margin for transient stability is not reduced significantly by the presence of the fault. Here too, the transfer reactance with the fault on is less than the transfer reactance with no fault and one line out of service.

Figure I-H illustrates the case for a three phase fault in the center of one of the lines. It shows that the system is capable of transferring some power while the fault is on, hence the margin for transient stability is increased as opposed to that for the three phase fault at the end of one of the lines where no power at all can be transferred.

The most serious threat with respect to stability is presented for a three phase fault at the terminals of one of the lines (Figure I-C). Thus it is imperative that the fault be cleared rapidly at the end near the fault. For faults closer to the center of the line, the system becomes capable of transferring some power across the lines, thus the stability margin will increase and an increase in relaying time can be tolerated.

The situation for single-line-to-ground faults is the least onerous and the margin for transient stability is increased considerably over that for three phase faults because of the lower transfer reactance. It was shown that the transfer reactance with a single-line-to-ground fault in the middle of one of the lines may be smaller than the transfer reactance with one line out of service. In light of this, the relaying times for single-line-to-ground faults are not critical from a point of view of system stability.

2. Short Lines, Weak Sources

The previous cases represent a system composed of long transmission lines with relatively stiff sources. Another system that can be studied is one composed of relatively short lines with weak sources. This might be the case where substations are located at the ends of the lines. The system parameters used to represent this situation are listed in cases 5 - 8 in Table 1. Figures I-J and I-K illustrate the power transfer curves for a three phase and a single-line-to-ground fault at the end of one of the lines. A three phase fault is the most onerous to the system, but the threat to stability does not diminish to any great degree as a function of fault location; i.e., the transfer reactance remains nearly constant for a fault anywhere on the line (see Table 1, cases 5 - 8). In this case, it is necessary for the relaying time to be nearly constant for a fault anywhere on the line. Loss of one of the short lines does not change the transfer reactance appreciably, thus the second line adds dependability to the system, but does not appreciably increase the power transfer capability or margin for stability. Once again, single-line-to-ground faults present the least onerous situation, but here too fault severity is relatively independent of fault location. Nearly constant relaying time would be desirable for faults of this type, although relaying time is not as critical as for three-phase faults.

3. Short Line in Parallel with Weak Interconnection

The final situation that will be studied is that of a short line paralleled by a relatively weak interconnection such as might be the case where a high voltage line is paralleled by a lower voltage interconnection. The system parameters are given in cases 9 - 12 of Table 1 for this system. Figures I-L and I-M represent the power transfer curves for a three phase and a single-line-to-ground fault at the end of the short line. Examination of the transfer reactances given in Table 1 show that they do not change significantly as a function of fault location for a given fault type. Thus, it is desirable to have nearly constant relaying time for a fault anywhere along the line. The transfer reactance does change significantly when the short line is taken out of service so that the power transfer capability decreases. This reduces the stability margin and it is imperative that rapid clearing of the fault be initiated.

Swing Angle Effects

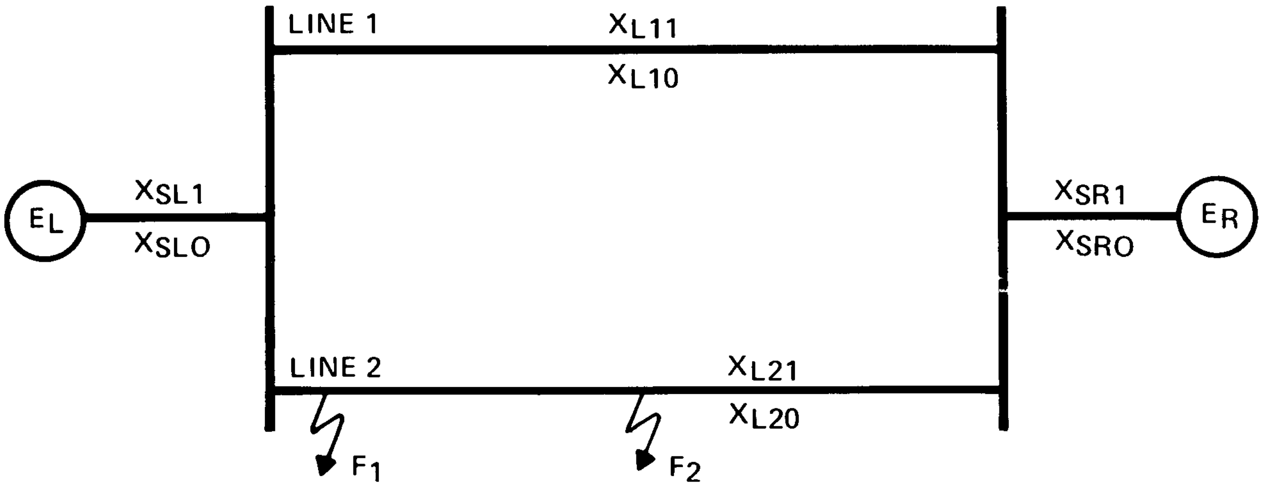
It was assumed throughout the previous discussion that the swing angle ($\delta_2 - \delta_1$) was equal for every fault type and fault location. In reality, the swing angle for other than three phase faults at the end of the line will be less than the assumed angle shown and will decrease as the severity of the fault decreases. This is so because the accelerating torque, which is proportional to the difference between the mechanical power input and the power transferred across the system, will decrease as the fault severity decreases. This in turn means that somewhat longer relaying times can be tolerated for other than three phase faults at the end of the line, while still maintaining the stability margin obtained for line-end three phase faults.

Summary

Three simple systems have been studied in terms of transient stability. The intent was not to determine the stability limits for a particular system, but rather to compare the relative effects on stability of varying system parameters. These studies do not purport to cover all system configurations, but they are sufficient to demonstrate that studies such as these can be used to establish the requirements of a relaying scheme that will meet the needs of the system. It can be seen that it is realistic to specify a minimum relaying operating time to meet the worst fault condition, but that it may be unrealistic to expect that time to be met for all fault types and all fault locations; i.e., somewhat longer tripping times can be tolerated for the less severe faults and fault locations.

TABLE 1

	SYSTEM PARAMETERS									TRANSFER REACTANCE X_T			
	LEFT SOURCE		LINE 1		LINE 2		RIGHT SOURCE			BOTH LINES	LINE 2	FAULT AT	FAULT AT
CASE	XSL1	XSLO	XL11	XL10	XL21	XL20	XSR1	XSR0	FAULT TYPE	IN	OUT	F_1	F_2
1	1	1	6	18	6	18	1	1	3ϕ	5.0	8.0	∞	13.33
2	1	1	6	18	6	18	1	1	$\phi - \phi - G$	5.0	8.0	14.4	7.87
3	1	1	6	18	6	18	1	1	$\phi - \phi$	5.0	8.0	10.0	7.27
4	1	1	6	18	6	18	1	1	SLG	5.0	8.0	7.34	5.81
5	4	4	1	3	1	3	4	4	3ϕ	8.5	9.0	∞	153
6	4	4	1	3	1	3	4	4	$\phi - \phi - G$	8.5	9.0	24.7	23.1
7	4	4	1	3	1	3	4	4	$\phi - \phi$	8.5	9.0	17.0	16.1
8	4	4	1	3	1	3	4	4	SLG	8.5	9.0	12.6	12.0
9	4	4	4	12	1	3	4	4	3ϕ	8.8	12.0	∞	396
10	4	4	4	12	1	3	4	4	$\phi - \phi - G$	8.8	12.0	25.4	23.8
11	4	4	4	12	1	3	4	4	$\phi - \phi$	8.8	12.0	17.6	17.2
12	4	4	4	12	1	3	4	4	SLG	8.8	12.0	12.9	12.6



$$P = \frac{E_L E_R \sin\delta}{X_T}$$

FIGURE I - A

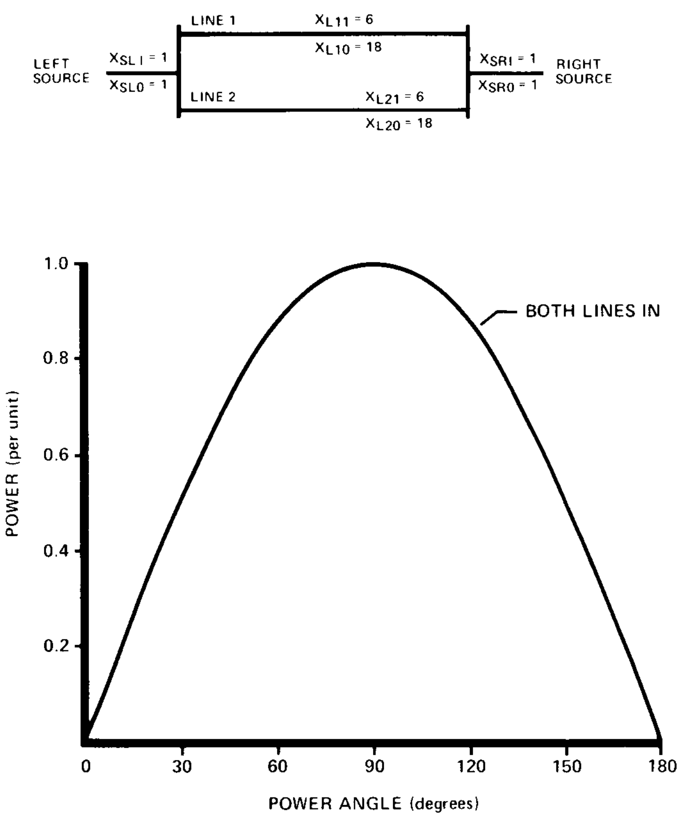


FIGURE I - B

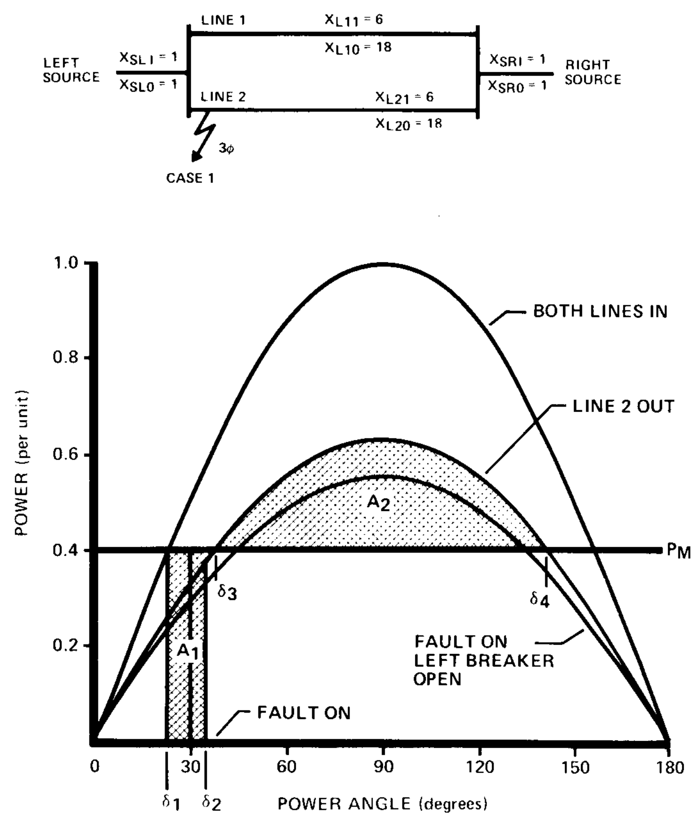


FIGURE I - C

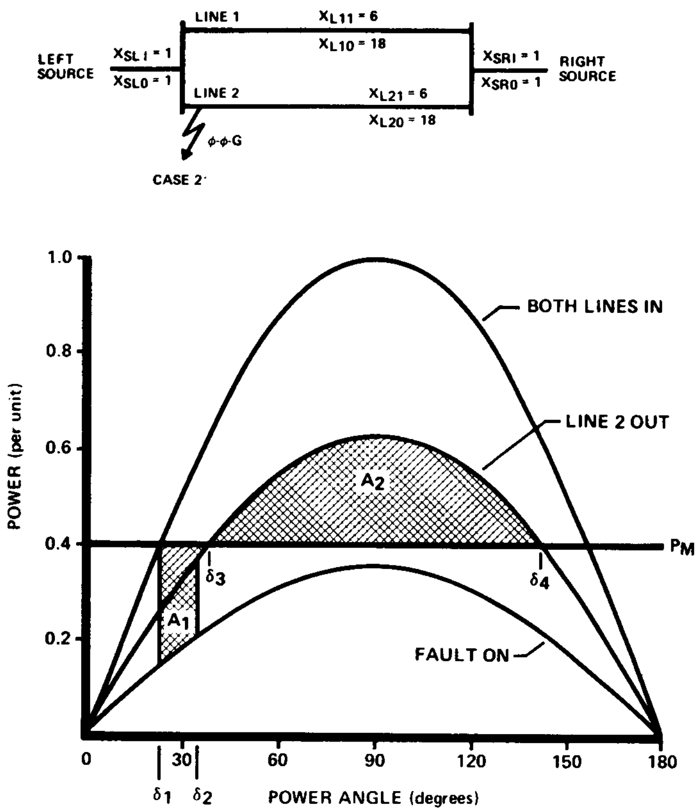


FIGURE I - D

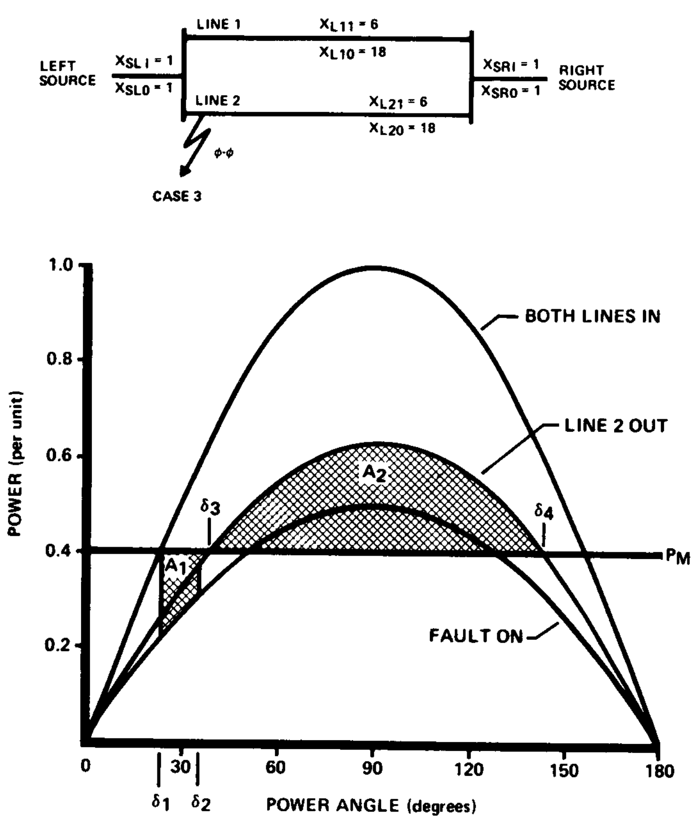


FIGURE I - E

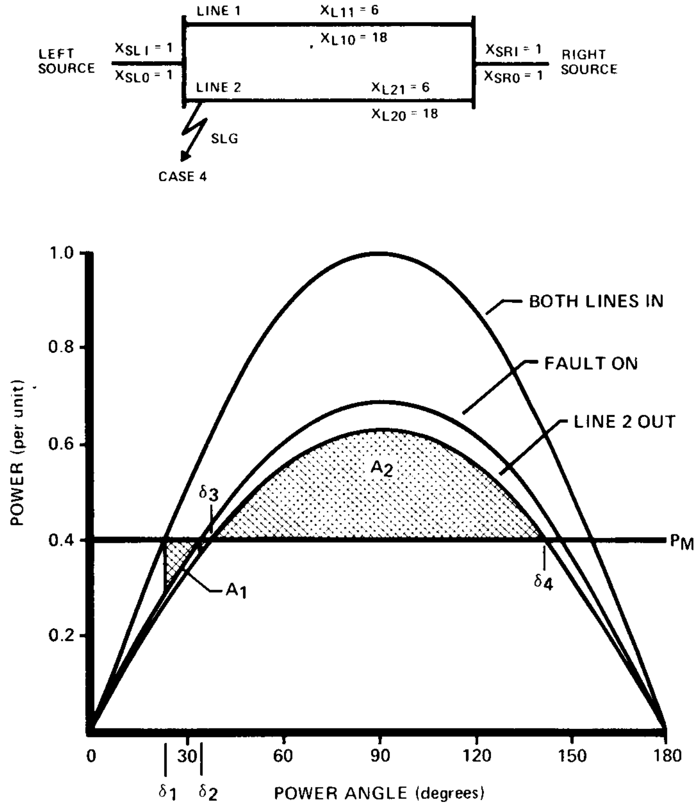


FIGURE I - F

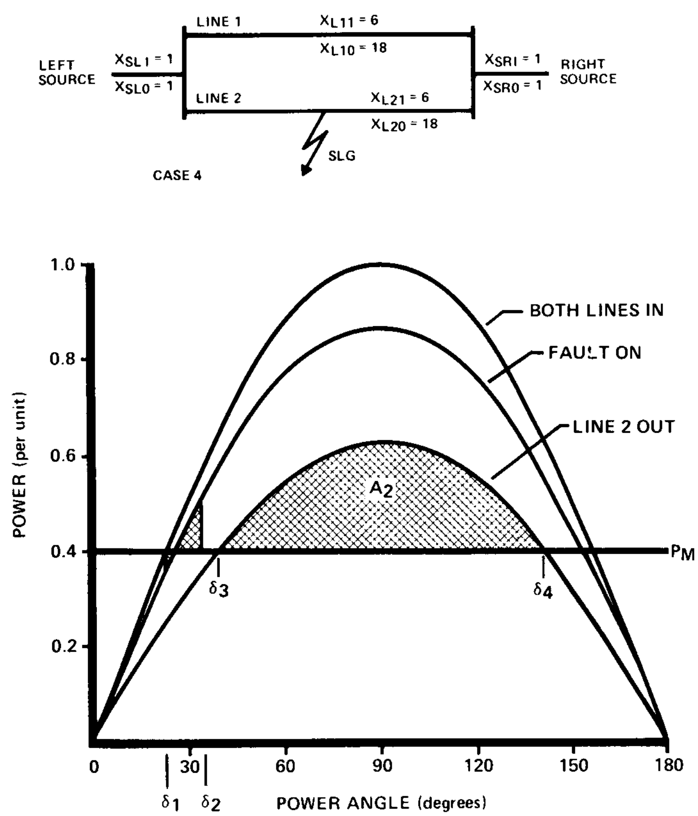


FIGURE I - G

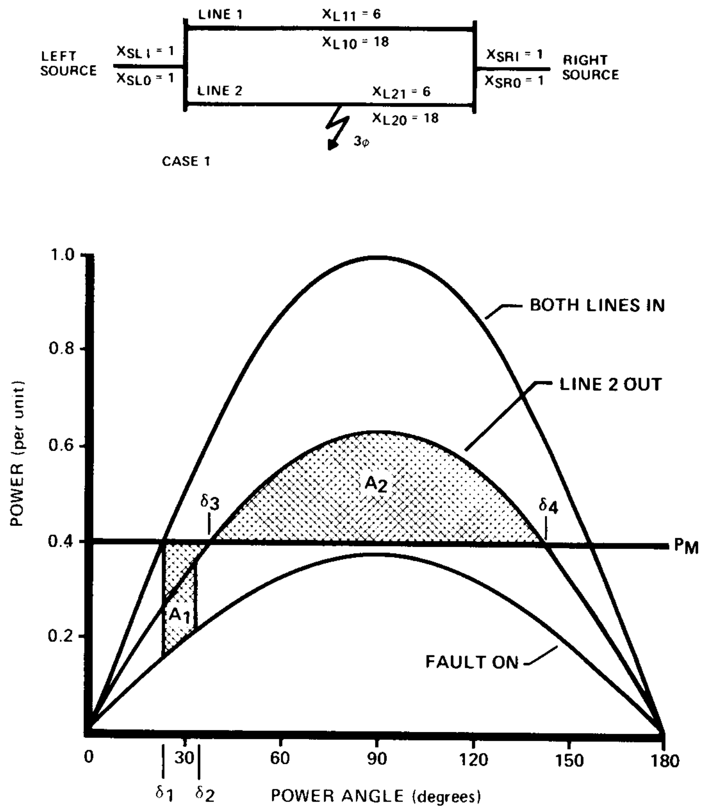


FIGURE I - H

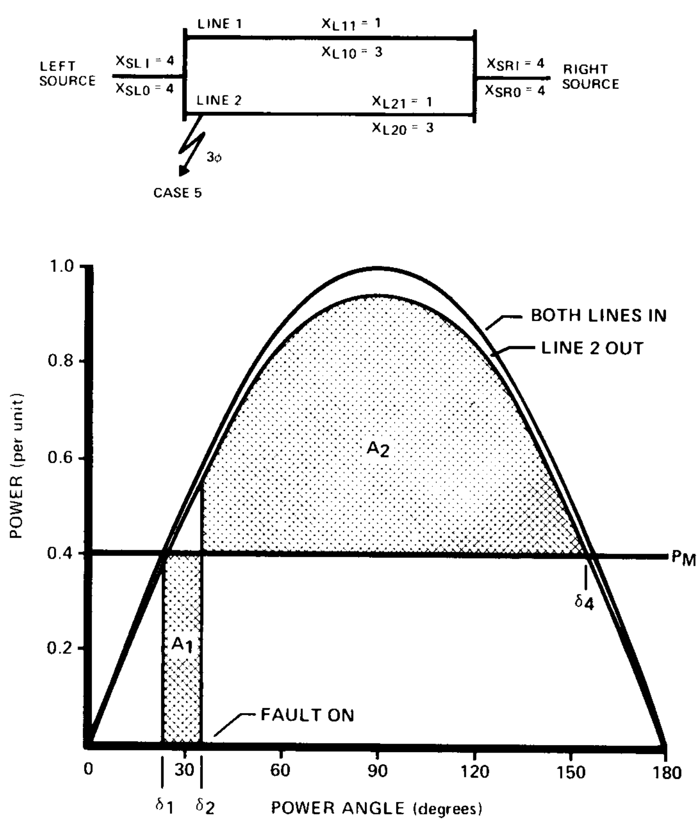


FIGURE I - J

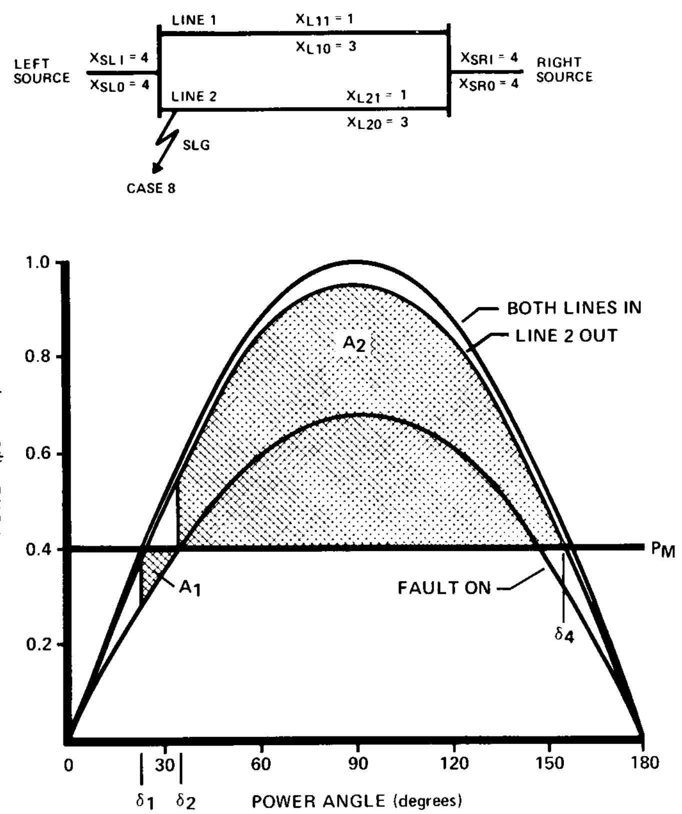


FIGURE I - K

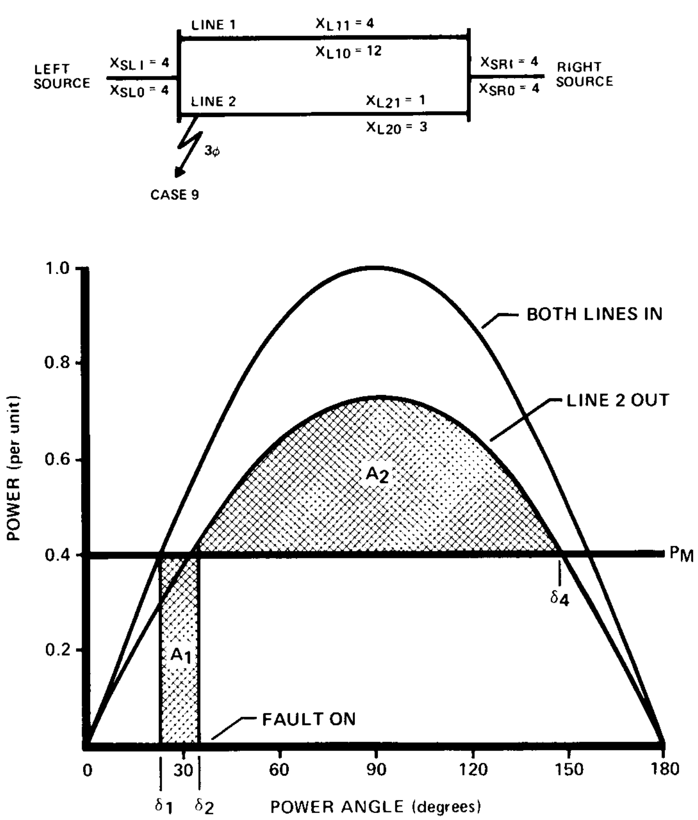


FIGURE I - L

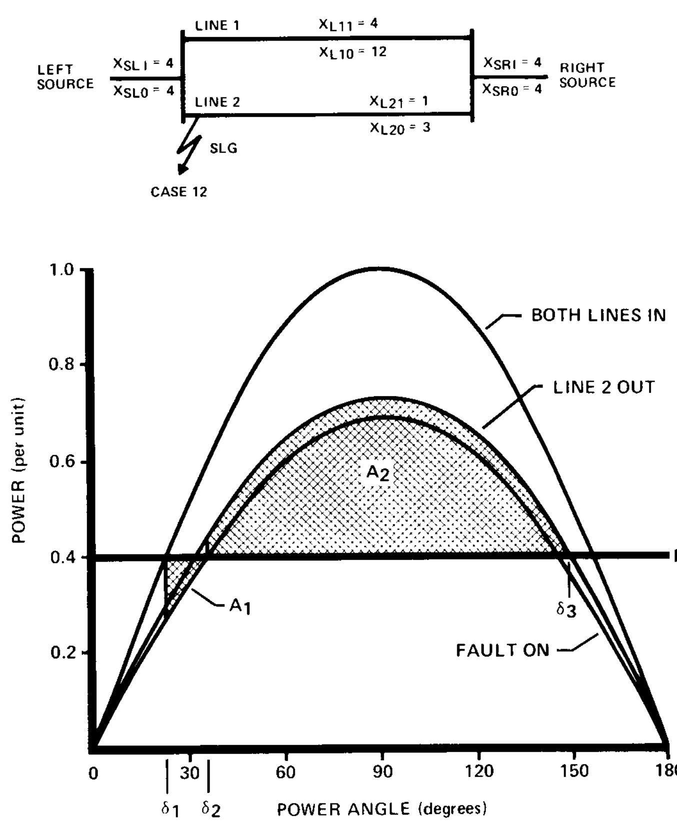
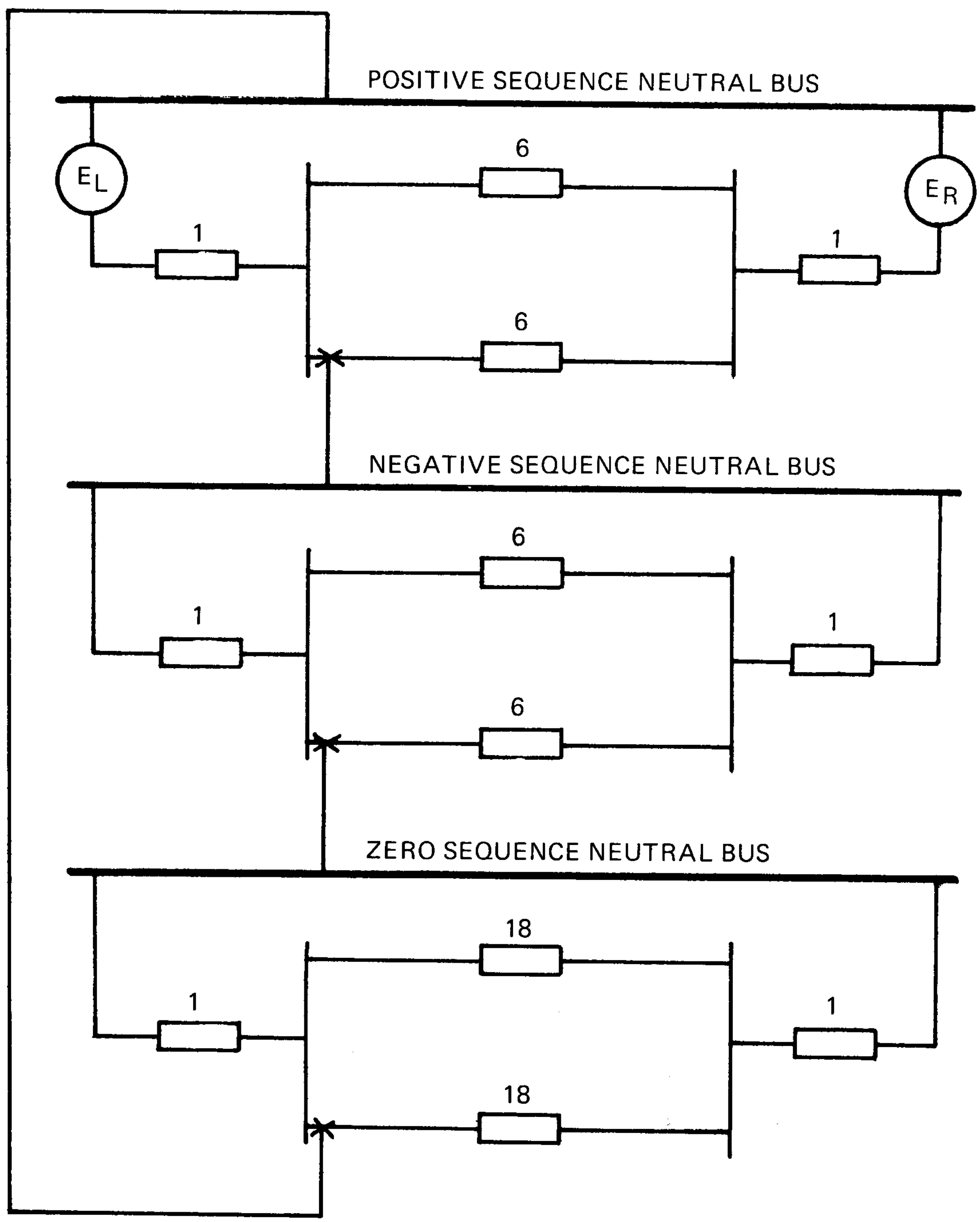


FIGURE I - M

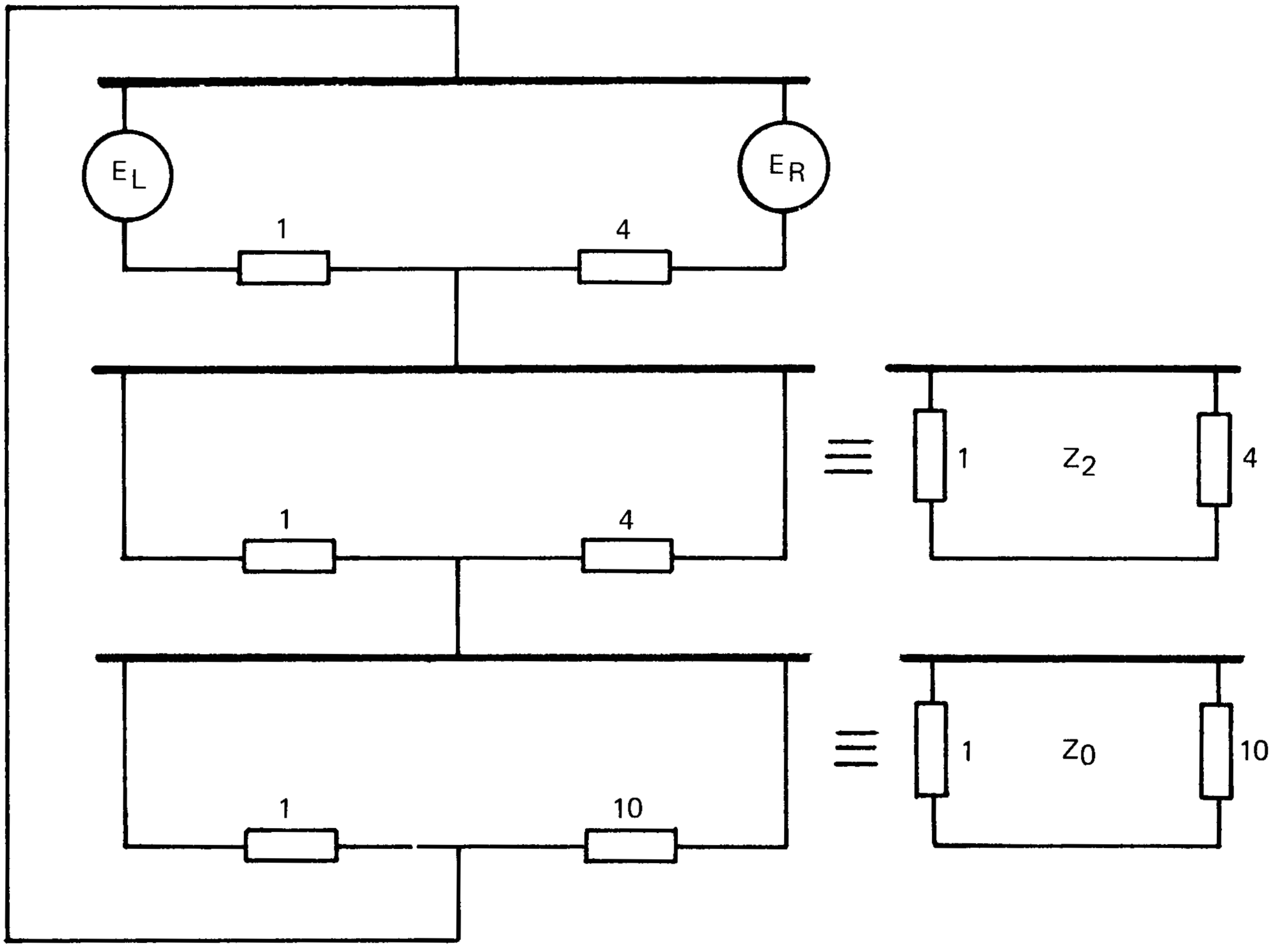
APPENDIX II

For the system shown in Figure I-F of Appendix I, the transfer impedance during the single-line-to-ground fault can be calculated as follows:

(A)

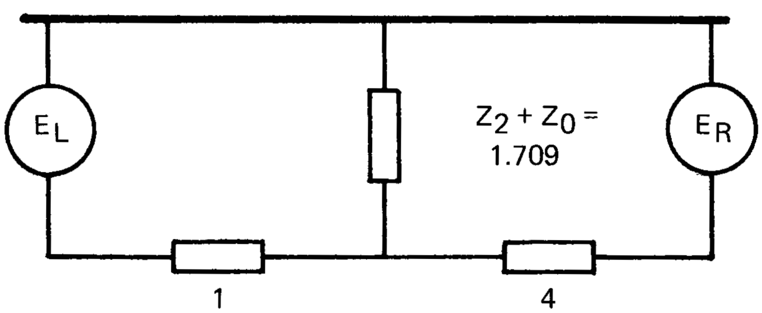


(B) By reduction ,

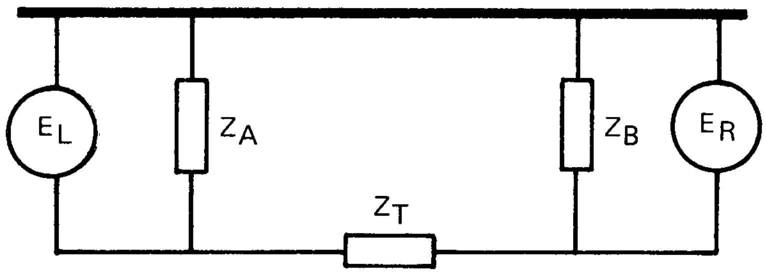


$$Z_2 = \frac{(4)\ (1)}{4 + 1} = 0.8 \qquad Z_0 = \frac{(10)\ (1)}{10 + 1} = 0.909$$

(C) Further reduction leads to,



(D) Finally, by wye - delta transformation,



Where:

$$Z_A = 1.709 + 1 + \frac{(1)\ (1.709)}{4} = 3.14$$

$$Z_B = 1.709 + 4 + \frac{(4)\ (1.709)}{1} = 12.55$$

$$Z_T = 1 + 4 + \frac{(1)\ (4)}{1\ .709} = 7.34$$

The equivalent transfer impedance between the two sources is Z_T = 7.34 Similar analysis can be used to calculate an equivalent transfer impedance for any system condition.

GE Power Management

215 Anderson Avenue
Markham, Ontario
Canada L6E 1B3
Tel: (905) 294-6222
Fax: (905) 201-2098
www.GEindustrial.com/pm