MULTILIN

GER-2681B

GE Power Management

Phase Comparison Relaying

PHASE COMPARISON RELAYING

INTRODUCTION

Phase comparison relaying is a kind of differential relaying that compares the phase angles of the currents entering one terminal of a transmission line with the phase angles of the currents entering all the remote terminals of the same line. For the conditions of a fault within the protected zone (internal fault), the currents *entering* all the terminals will be in phase. For conditions of a fault outside the zone of protection (external or through fault), or for just plain load flow, the currents *entering* any one terminal will be 180 degrees out of phase with the currents *entering* at least one of the remote terminals. The phase comparison relay scheme makes this phase angle comparison and trips the associated breakers for internal faults. Since the terminals of a transmission line are normally many miles apart, some sort of communication channel between the terminals is required to make this comparison.

FUNDAMENTAL PRINCIPLE OF PHASE COMPARISON

The basic operation of a phase comparison scheme requires that the phase angle of two or more currents be compared with each other. In the case of transmission line protection, these currents may originate many miles from each other so, as noted above, some form of communication channel is required as part of the scheme. If a two-terminal line is considered, the relays located at terminal A can measure the current at that terminal directly. The phase angle of the current at the remote terminal (B) must somehow be communicated to terminal A. Since the current sine wave is positive for one half cycle and then negative for the next half cycle etc., it may be used to key a transmitter first to a MARK signal for a half cycle and then to a SPACE signal for the next half cycle for as long as the current is present. Such a signal transmitted at B and received at A can be compared with the current at A to determine whether the two quantities are in phase or out of phase with each other. Conversely, the current at terminal B may be compared with the signals received from terminal A.

It becomes apparent that a comparison such as that described above must be made on a single phase basis. That is, it would not be possible to compare all three phase currents at terminal A individually with all three at terminal B over one single channel and one single comparing unit. Thus, in the interest of economy, all three phase-currents are mixed to produce a single phase quantity whose magnitude and phase angle have a definite relation to the magnitude and phase angle of the three original currents. It is this single phase quantity that is phase compared with a similarly obtained quantity at the remote end(s) of the line.

While there are many variations on the basic scheme (and these will be discussed subsequently), the general method employed to compare the phase angle, or phase position of the currents is always the same. The left side of Figure 1 illustrates the conditions for a fault internal to the protected zone. The top sketch shows about 1 cycle of the current flowing *into* terminal A. The second sketch down indicates the current flowing *into* terminal B. These are in phase since the fault is internal. The third sketch down represents the receiver output at terminal A as a result of the transmitter at B being keyed from a signal produced by the current at that terminal.

The MARK-SPACE designations given to the received signal are for identification and have no special significance. If the communication equipment happened to be a simple radio frequency transmitter-receiver, and if the positive half cycle of current keyed the transmitter to ON, then the MARK block would correspond to a received remote signal while the SPACE block would correspond to no signal. Conversely, if the negative portion of the current wave keyed the transmitter to ON, then the SPACE block would represent the received signal.

With a frequency-shift transmitter-receiver as the communication equipment, the MARK block would represent the receipt of the hi-shift frequency and the SPACE block the lo-shift frequency if the remote transmitter were keyed to high from a positive current signal. The converse would be true if the transmitter were keyed to high from a negative current signal. In any case the MARK block received at A, whatever it represents, corresponds to positive current at B while the SPACE block corresponds to negative current at B.

If we consider an internal fault as shown on the left side of Figure 1, the relay at A would be comparing quantities illustrated in the top and third-from-the-top sketches. If these two signals at terminal A were to be compared as shown in Figure 2A over a frequency-shift equipment, a trip output would occur if positive current and a receiver MARK signal were both concurrently and continuously present for at least 8.33 milliseconds. The trip output would be continued for 18 milliseconds to ride over the following half cycle during which the current is negative, and the half cycle after that when the pick-up timing takes place again.

Assuming that the MARK and SPACE signals cannot both be present concurrently then it might be argued that a comparison could be made between the positive half cycle of current and the *absence* of a receiver SPACE output, Figure 2B illustrates this logic.

If the communication equipment happened to be a frequency shift channel so that both the MARK and the SPACE signals were definite outputs, Figure 2A would represent a tripping scheme since tripping is predicated on the receipt of a remote MARK or tripping signal. On the other hand, Figure 2B would represent a blocking scheme in as much as it will block tripping in the presence of a SPACE or blocking signal. It will trip only in the absence of this signal.

The right side of Figure 1 illustrates the conditions during an external fault. Referring to Figures 2A and 2B it will be noted that neither approach, the blocking or the tripping, will result in a trip output for this condition since the AND circuits will never produce any outputs to the 8.33/18 timers.

At this point it should be explained that the conditions illustrated in Figure 1 are ideal. They seldom, if ever, occur in a real power system. Actually an internal fault would *not* produce a received signal MARK-SPACE relationship that is *exactly* in phase with the locally contrived single phase current. This is true for a variety of reasons including the following:

(a) Current transformer saturation.

(b) Adjustment differences in the current mixing networks in the relays at both ends of the line.

(c) Phase angle differences between the currents entering both ends of the line as a result of phase angle differences in the driving system voltages.

(d) Transit time of the communication signal.

(e) Unsymmetrical build-up and tail-off times of the receiver.

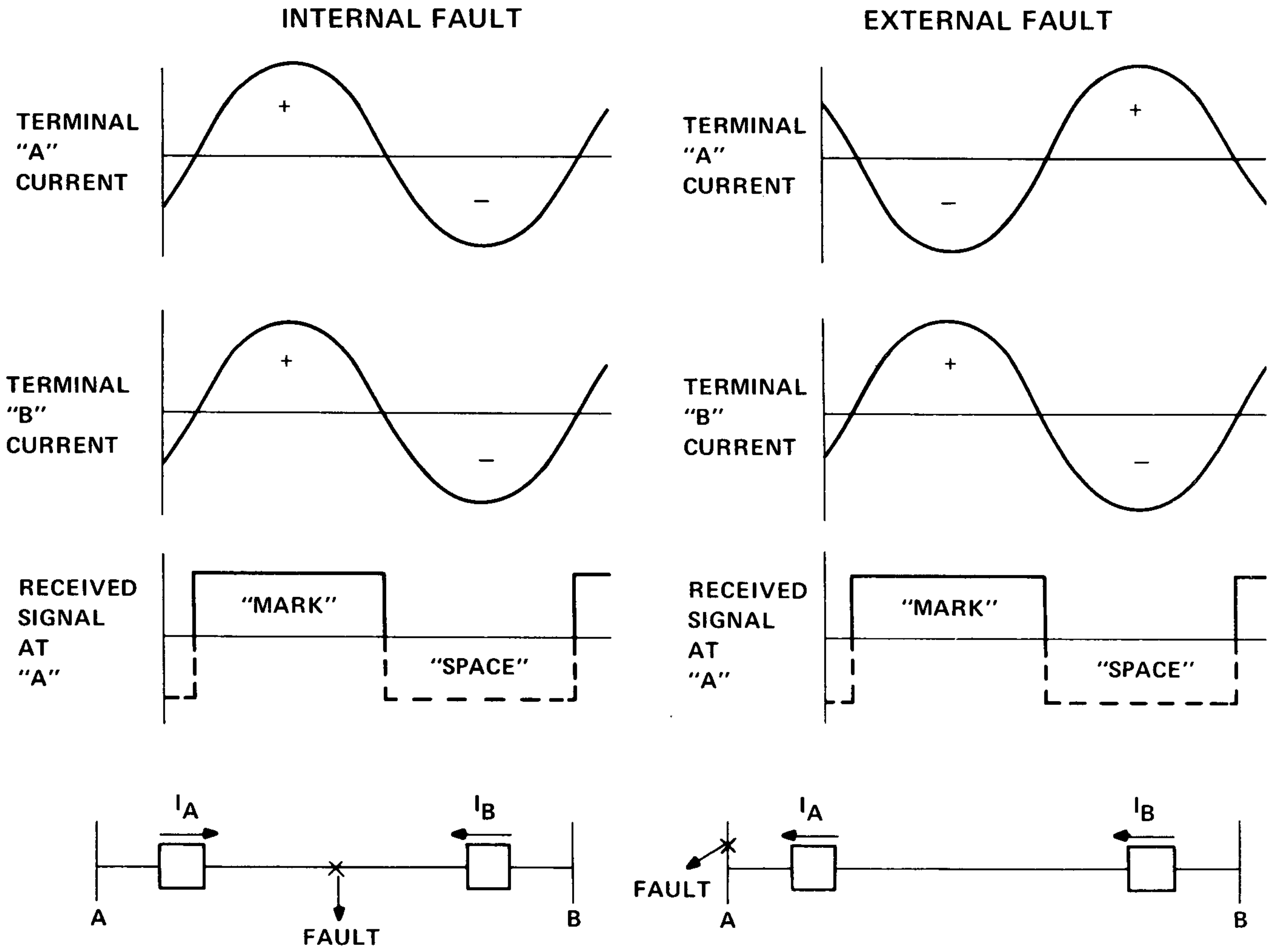


Figure 1. Phase Angle Comparison

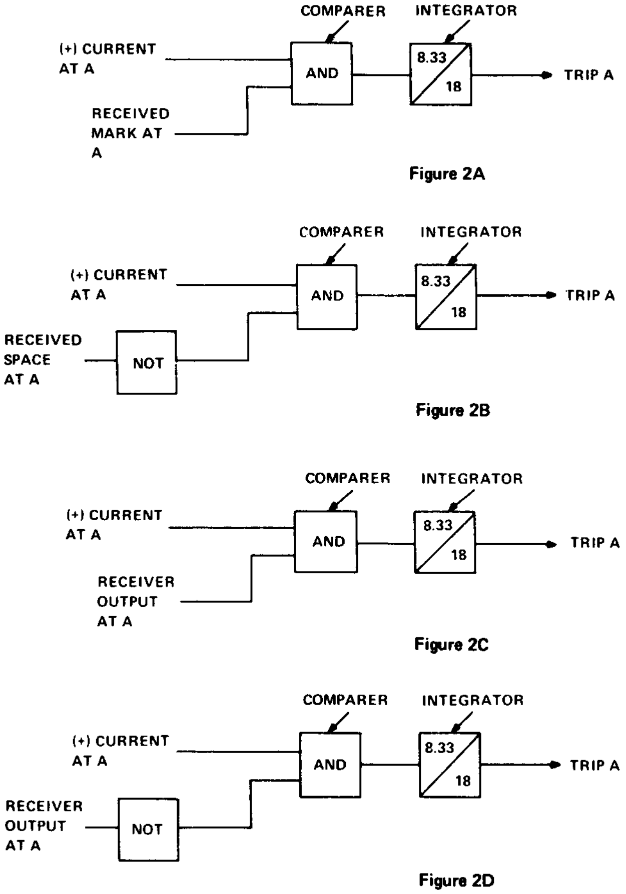


Figure 2A

Figure 2B

Figure 2C

Figure 2D

Figure 2. Two Terminal Line Phase Comparison

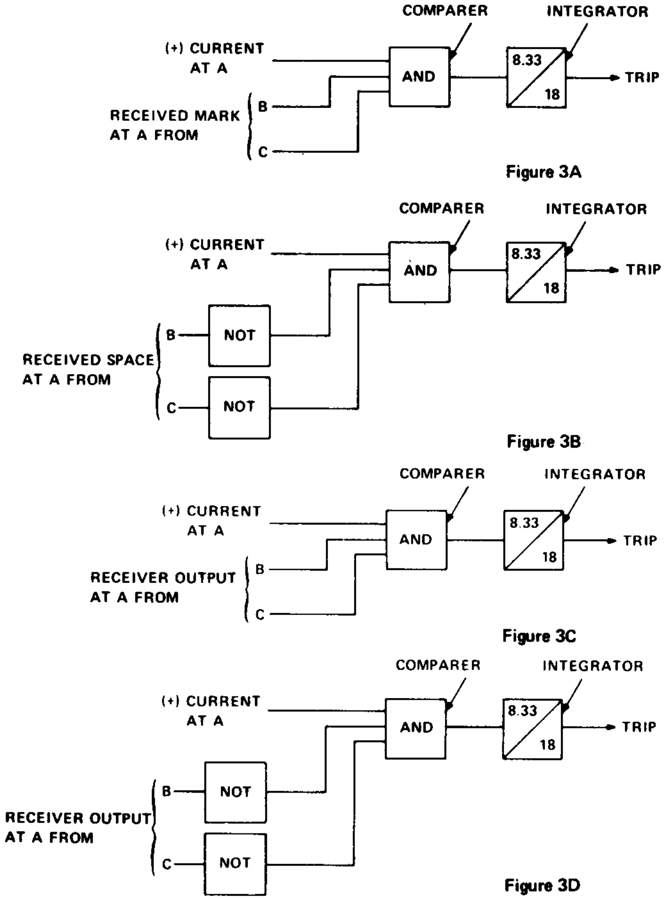


Figure 3A

Figure 3B

Figure 3C

Figure 3D

Figure 3. Three Terminal Line Phase Comparison

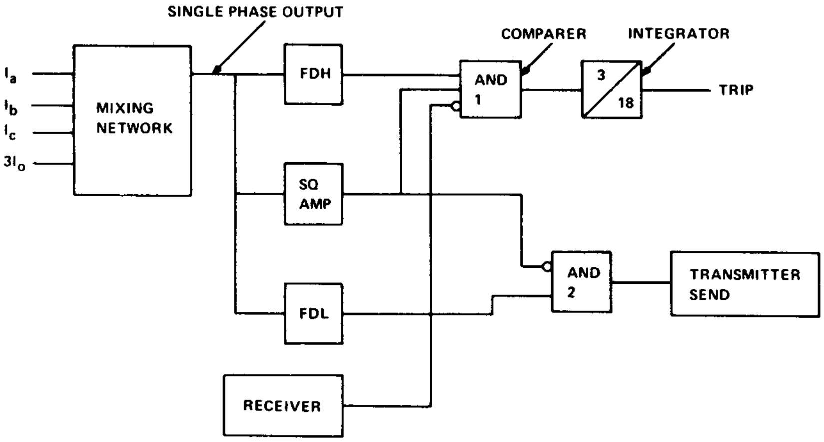


Figure 4. Single Phase-Comparison Blocking Scheme

Thus, the logic shown in Figures 2A and 2B would rarely, if ever, produce a trip output on an internal fault because the 8.33 milliseconds (which is the time of a half cycle on a 60 hertz base) requires perfect matching. In actual practice a 3-4 millisecond setting is used rather than the 8.33 setting illustrated. This makes it much easier to trip on internal faults. It also makes it much easier to trip undesirably on external faults. However, experience has indicated that with proper settings and adjustments in the relay such a timer setting offers an excellent compromise. This may be better appreciated if it is recognized that item (a) above is generally minimized and item (c) is nonexistent on external faults.

In the event that an ON-OFF communication equipment were to be employed rather than the frequency-shift equipment, the logic would appear as in Figures 2C and 2D. It will be noted in these two figures that the reference to MARK and SPACE have been conveniently omitted since the receiver output is either present or not as against the case of the frequency-shift equipment where it could be there in either of two states. Figure 2C illustrates a tripping scheme while Figure 2D a blocking scheme. Here again, the 8.33 millisecond timer is, in practice, actually set for 3-4 milliseconds.

Figures 3A, 3B, 3C, and 3D are for three-terminal lines and they correspond directly to Figures 2A, 2B, 2C, and 2D. It will be noted from Figure 3 that for a three-terminal line, the relay at A must receive information from both the remote terminals. The same applies to the relays at terminals B and C. As in the case of the two-terminal lines, the 8.33 millisecond timer illustrated in Figure 3 will actually be set for 3-4 milliseconds.

While all the sketches in Figures 2 and 3 compare the positive half cycle of current with a receiver output, the negative half cycle might just as well have been selected. However, if this were done, in Figure 2A for example, it would have been necessary to compare the presence of negative current with a received SPACE signal rather than a MARK signal.

It should be recognized that the above discussion, as well as Figures 2 and 3, are rudimentary. The complete phase comparison scheme is considerably more sophisticated and will be discussed in more detail subsequently. However, at this point it would be well to note that phase comparison on a continuous basis is not permitted mainly because it would tend to reduce the security of the scheme. For this reason fault detectors are provided. They initiate phase comparison only when a fault occurs on, or in the general vicinity of, the protected line. A simplified sketch of the logic of a phase comparison blocking scheme including fault detectors is illustrated in Figure 4. This is a somewhat more fully developed version of Figure 2D, and the same logic is present at both ends of a two-terminal line.

It will be noted from Figure 4 that AND1 (the comparer) at each end of the line compares the coincidence time of the positive half cycle of current with the absence of receiver output. This is initiated only when a fault is present as indicated by an output from FDH. FDH is set so that it does not pick up on load current but does pick up for all faults on the protected line section. Thus, when a fault occurs FDH picks up, and if the receiver output is not present for 3 milliseconds during the positive half cycle of current out of the mixing network, a trip output will be obtained.

Of course, the output from the receiver will depend on the keying of the remote transmitter. The transmitters at all line terminals are keyed in the same manner. They are keyed ON by an output from FDL and keyed OFF by the squaring amplifier via AND2 during the positive half cycles of current. The FDL function is required at all terminals in all phase comparison blocking schemes to initiate a blocking signal from the associated transmitter. This is received at the remote receiver and blocks tripping via the comparer during external faults. FDL has a more sensitive setting and therefore operates faster than the remote FDH function. It is obvious from Figure 4 that if an external fault occurred, and FDL did not operate at least as fast as the remote FDH, false tripping could occur because of the lack of receiver output. In general FDL is set so as not to pick up on load current but still with a lower pick up than FDH so that it will operate before FDH. For an internal fault, the currents entering both ends of the line are in phase with each other. Thus, during the half cycle that the SQ AMP is providing an input to AND1, the associated receiver is producing no output, and so tripping will take place at both ends of the line. For an external fault, the current entering one terminal is 180 degrees out of phase with the current entering the other terminal. Under these conditions, during the half cycles when the SQ AMP is producing outputs, the associated receiver is also providing an output thus preventing an AND1 output. No tripping will take place.

VARIATIONS IN PHASE COMPARISON SCHEMES

There are a number of different phase comparison schemes in general use today and while all of these employ the same basic means of comparison described above, significant differences do exist. These differences relate to the following:

(1) Phase comparison excitation (component or current to be compared).

(2) Pure phase comparison vs. combined phase and directional comparison.

(3) Blocking vs. tripping schemes.

(4) Single vs. dual phase comparison.

PHASE COMPARISON EXCITATION

Before discussing this subject it is well to consider what takes place in terms of the currents that are available for comparison when a fault occurs on a power system. Table I below lists the sequence components of fault current that are present during the various different kinds of faults while Figure 5 illustrates the relative phase positions of the sequence components of fault current for the different kinds of faults and the different phases involved.

TABLE I

	Sequence Components		
Type of Fault	Positive	Negative	Zero
Single-Phase-to-Ground	yes	yes	yes
Phase-to-Phase	yes	yes	no
Double-Phase-to-Ground	yes	yes	yes
Three-Phase	yes	no	no

Figure 5 shows the relative phase positions of the outputs of a positive sequence network, a negative sequence network, and a zero sequence network all referenced to phase A. The transfer functions of these three networks are given by the following equations.

$$I_1 = \frac{1}{3} \left(I_a + I_b\underline{/120^\circ} + I_c\underline{/-120^\circ}\right) \qquad (1)$$

$$I_2 = \frac{1}{3} \left(I_a + I_b\underline{/-120^\circ} + I_c\underline{/120^\circ}\right) \qquad (2)$$

$$I_0 = \frac{1}{3} \left(I_a + I_b + I_c\right) \qquad (3)$$

It is interesting to note that the phase positions of the sequence network outputs differ depending on the phase or phases that are faulted as well as the type of fault. For example, while the positive, negative, and zero sequence components are all in phase for a single-phase-A-to-ground fault, they are 120 degrees out of phase with each other for phase-B-to-ground, and phase-C-to-ground faults.

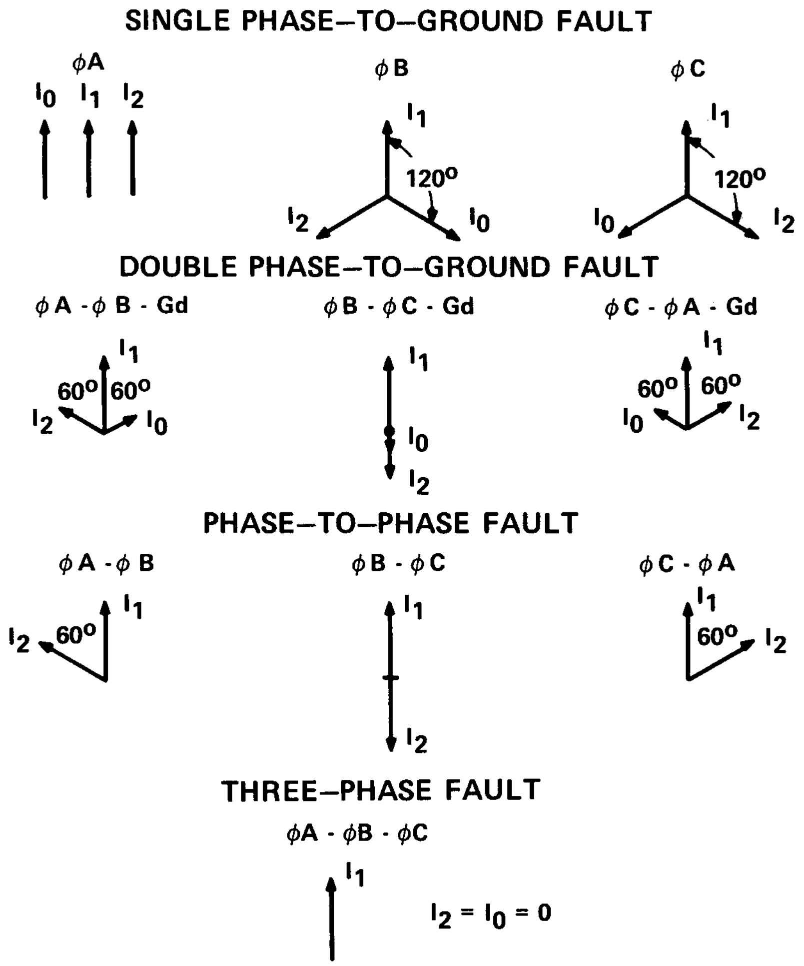


Figure 5. Sequence Network Outputs

It will be observed from Table I that positive sequence currents are available for all kinds of faults, negative sequence currents are available for all but three-phase faults, and zero sequence currents are available only for faults involving ground. Thus, it appears that if one single sequence component of current were to be selected for use to make the phase comparison, the positive sequence component would suffice. Actually this is *not* the case in many if not most of the applications because of the presence of through load current during the fault.

For a single-phase-to-ground fault on the protected line, the positive sequence component of *fault* current *entering* one end will be in phase with that *entering* the other end. This is a tripping situation for the phase comparison scheme. However, any load flow across the line during the fault will produce a positive sequence component of *load* current *entering* one end of the line that is 180 degrees out of phase with that *entering* the other end. (That is, the positive sequence component of load current *entering* one end is in phase with that *leaving* the other end). This is a non-tripping situation for the phase comparison scheme. The phase position of the load component relative to the fault component depends on such factors as the direction of the load flow, power factor of the load flow, and the phase angles of the system impedances. The phase position of the "net" (load plus fault) positive sequence current entering one end of the line relative to that entering the other end will depend on these same factors plus the relative magnitude of the fault and load components of current.

In general, the heavier the fault current, and the lighter the load current, the more suitable is the use of pure positive sequence for phase comparison. Heavier line loadings and lower fault currents will tend to make the scheme less apt to function properly for internal faults. Thus, pure positive sequence phase comparison appears practical only in a minority of the cases and so is not suitable for a scheme that is to be generally applicable.

Significant negative sequence currents are present only during faults, they are present in all but balanced three phase faults, and there is no significant negative sequence component of load current. All this combines to make pure negative sequence ideal for phase comparison except that it will not operate for balanced three phase faults. Similar comments may be made regarding pure zero sequence phase comparison with the additional limitation that it will not operate for phase-to-phase faults. Thus, there does not appear to be one single sequence component or one single phase current that could be used in a phase comparison scheme to protect against all types of faults.

There are a number of different approaches that are possible to provide a complete scheme. Probably the most obvious would be to make the phase comparison on each phase separately. This is undesirable principally because the cost would be high since three separate phase comparison relays and communication sets would be required. Another approach would be to use two separate phase comparison relays and communication sets, one for pure positive and the other for pure negative sequence currents. The latter would serve to protect against all unbalanced faults while the former would take care of three phase faults and also provide a measure of back-up protection for heavy unbalanced faults. Here again cost is an important factor.

As soon as consideration is given to the use of a separate positive and a separate negative phase sequence comparison, the idea of switching from one to the other presents itself. Such schemes are available. They include detectors separate from the phase comparison function that distinguish between three phase faults and all other types. For three phase faults the negative sequence network is unbalanced so that it produces an output for positive sequence current as well as for negative sequence current. The scheme operates normally to provide negative sequence phase comparison for all unbalanced faults. When a three phase fault occurs the three-phase detectors at both ends of the line operate to automatically unbalance their respective negative sequence networks and make them sensitive to positive as well as negative sequence currents. Since the fault is three phase, there is no negative sequence current produced so the phase comparison is made on a pure positive sequence basis. This is all accomplished with a common communication channel for both modes.

Another similar approach would be to provide two separate sequence networks, one pure positive sequence and the other pure negative sequence. Then use the three-phase detector to switch the logic so that only for three phase faults the outputs of the positive sequence networks at both ends of the line are compared but for all other faults the negative sequence outputs are compared. Here again all this being accomplished over a common channel. This approach has never been used possibly because of the idea of using "Mixed Excitation."

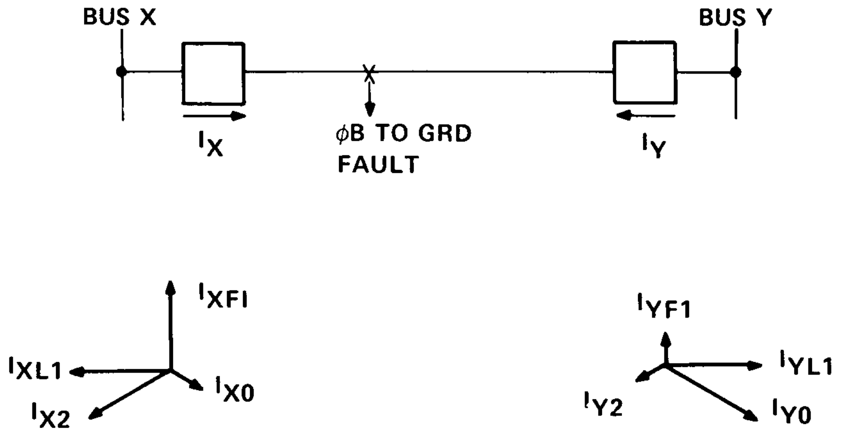
Mixed Excitation is a term used to describe a phase comparison scheme that mixes the outputs of the different sequence networks in a given proportion and phase angle and then makes a phase comparison for all faults based on this mix. Thus, all such schemes must include positive sequence plus negative sequence and/or zero sequence in order to operate for all faults. The two main questions to be resolved are:

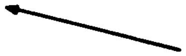
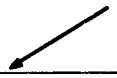
(1) Which sequence components should be mixed with the positive sequence.

(2) What percentages of the full magnitude of each sequence component of current should be used.

Figure 6 illustrates a two-terminal line with an internal phase B-to-ground fault. The phasor diagrams at the top of the page indicate the phase positions of the sequence currents at both ends-of the line assuming the positive direction of current flow into the line, and also assuming phase A reference as in equations (1), (2), and (3) previously given.

At this point it should be recognized that the positive sequence component of current is made up of two parts, the load component (I_{L1}) and the fault component (I_{F1}). By an analysis utilizing superposition the load component (I_{L1}) may be established as the current flowing just prior to the fault. The three fault components of current (I_{F1}, I_2 and I_0) are then calculated using the voltage that existed at the point of fault just prior to the fault. Since the load component of current is equal to the vector difference between Bus X and Bus Y voltages divided by the impedance of the line, and since the prefault voltage (at the point of fault) has a phase position somewhere between that of X and Y voltages, the positive sequence component of fault current will be displaced from the load component by about 90 degrees plus or minus about 30 degrees. The phasor diagrams at the top of Figure 6 assume that load current flow is from bus X to bus Y. The first row of the table in Figure 6 indicates that for the conditions assumed, the net positive sequence current *entering* both ends of the line are about 120 degrees displaced from each other. Heavier fault current and lighter load current would reduce this angle toward zero while the converse would increase the angle toward 180 degrees.



SEQUENCE MIXTURE	I_X	I_Y	ANGLE BETWEEN I_X AND I_Y
PURE I_1			120°
$I_1 + I_2$			155°
$I_1 + I_2 + I_0$			180°
$I_2 - \frac{I_1}{5}$			35°
$I_2 - I_0 - \frac{I_1}{5}$			40°

I_{XLI} = Pos. Sequence Load Component
I_{XFI} = Pos. Sequence Fault Component
I_{XI} = $I_{XLI} + I_{XFI}$
} Same Applies to I_Y

Figure 6. Vector Relationships In A Two-Terminal Faulted Line (Phase B—to—Ground)

The second and third rows of the table of Figure 6 indicates the relative phase positions of the positive plus negative, and positive plus negative plus zero sequence components respectively. These appear to be more unsatisfactory. Rows 4 and 5 combine the components differently and both appear to yield much better results.

It is obvious, from Figure 5 that a similar fault on a different phase would yield different results. This is illustrated in Figure 7 where a phase-A-to-ground fault at the same location is analyzed. As noted earlier, the integrator timers in phase comparison schemes are generally set for about 3 milliseconds. This will permit tripping on internal faults with as much as 115 degrees between the phase angles of the currents entering both ends of the lines. On this basis, only excitation by I_2 - $I_{1/5}$ would prove satisfactory for the two cases studied in Figures 6 and 7.

Actually only two simple faults were investigated. It is obvious that different results would have been obtained for these same kind of faults if the relative magnitudes of load current, positive sequence fault current, and zero sequence fault current had been assumed differently. Also, for the values of currents assumed, different results would obtain for other types of faults. In addition, if different combinations and weighting factors of the sequence components had been investigated still different answers would have resulted. In the proper selection of sequence components and weighting factors for Mixed Excitation phase comparison the following points must be considered:

(a) Whatever combination and weighting factors are employed, the application rules should be simple enough to make the application practical.

(b) As a corollary to (a) above, the fewest number of sequence components should be used.

(c) The effects of load current must be minimized. Thus, negative and/or zero sequence components should be weighted over the positive sequence components.

(d) The limits of application should be broad enough to render the scheme useful as a protection tool.

In line with the considerations stipulated above, the best overall results using mixed excitation would be attained by using I_2 - I_1/K, where K is a constant that is adjustable within limits. While it is likely that the inclusion of zero sequence excitation would be helpful for one case or another, it is not generally employed because the problem of evaluating the overall performance of the scheme would be magnified considerably. This is true mainly because the current distribution in the zero sequence network is generally quite different from that in the positive and negative sequence networks where the current distributions are approximately the same. For any given fault on a transmission line, the ratio of I_{F1}/I_2 at any terminal is the same as at any other terminal of that line. This is not true of either I_{F1}/I_0 or I_2/I_0. It is this that makes the use of zero sequence excitation undesirable.

Mixed Excitation Phase Comparison

If the mixing network of Figure 4 were designed to produce an output that is proportional to $I_2 - I_1$/K, this logic would then be a simplified representation of a mixed excitation phase comparison scheme. In such schemes, the pick up setting of FDH must be high enough so that the I_1/K output from the mixing network does not result in continuous phase comparison on load current (I_2 is normally zero during normal system conditions). Also, it may be desirable to have FDL set to pick-up at some level above full load so that channel is not keyed on and off continuously during normal load conditions.

Since FDH is set higher than FDL, this requirement results in a still higher setting for FDH.

Because FDH controls tripping, this arrangement limits the applicability of the basic scheme to circuits where the minimum three phase fault current is significantly higher than the maximum load current.

The requirements for the satisfactory performance of a mixed excitation scheme using overcurrent fault detectors (FDH and FDL) are noted below.

(a) Both the FDL and FDH fault detectors must be set above full load current.

(b) All internal faults regardless of type or the particular phases involved must produce enough $I_2 - I_1/K$ to operate FDH at all ends of the line.

(c) FDL must be set with a lower pick-up than FDH at the remote end(s) of the line for security during external faults.

(d) The phase angle difference between the $I_2 - I_1/K$ quantities obtained at all terminals of the protected line during all types of internal faults, and for any combination of phases, must be less than 115 degrees.

Mho Supervised Mixed Excitation Phase Comparison

Figure 8 is an abbreviated logic diagram covering a modified mixed excitation blocking scheme that provides somewhat more sensitivity than the basic scheme. In order to accomplish this, two single-phase directional mho distance measuring functions are used. These are both associated with the same pair of phases which, in this case, are phases A and B. The MT function at each terminal "looks" into the line and is set to reach beyond the remote terminal(s). The MB function "looks" backwards, out of the line and is set to reach beyond the reach of the remote MT function(s). These functions are required to operate for three phase faults but will incidentally also operate for some other faults involving one or both of the associated phases.

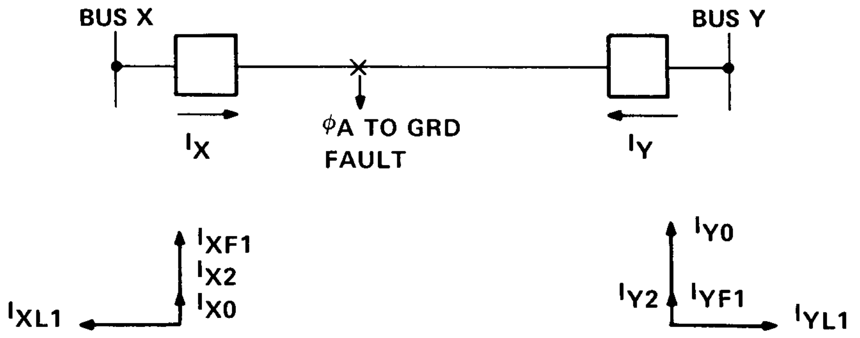
The basic idea is to compare the relative phase positions of the *mixed excitation* ($I_2 - I_1/K$) in the normal manner but to initiate the comparison with more discriminatory fault detectors. To accomplish these ends, pure negative sequence is used to operate FDH and FDL. Since there is no significant negative sequence current flowing during normal system conditions, these fault detectors may be applied with very sensitive settings. They will initiate phase comparison for all except three-phase faults. In the event of three phase faults the MT and MB units function as FDH and FDL respectively. Since these functions can discriminate between load currents and fault currents regardless of magnitudes, they can detect faults that produce currents less than full load values. Thus, the combination of negative sequence current level detectors and distance measuring functions provide a means for more sensitive fault detection.

With this arrangement, the requirements for satisfactory performance are given below.

(a) The FDH function must be set sensitively enough to pick up for all unbalanced faults on the protected line section.

(b) FDL must be set with a lower pick up than FDH at the remote end(s) of the line for security during external faults.

(c) The MT function must be set with a long enough reach to detect all internal three phase faults.



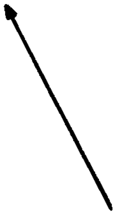
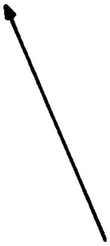
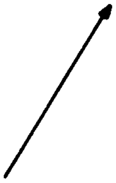
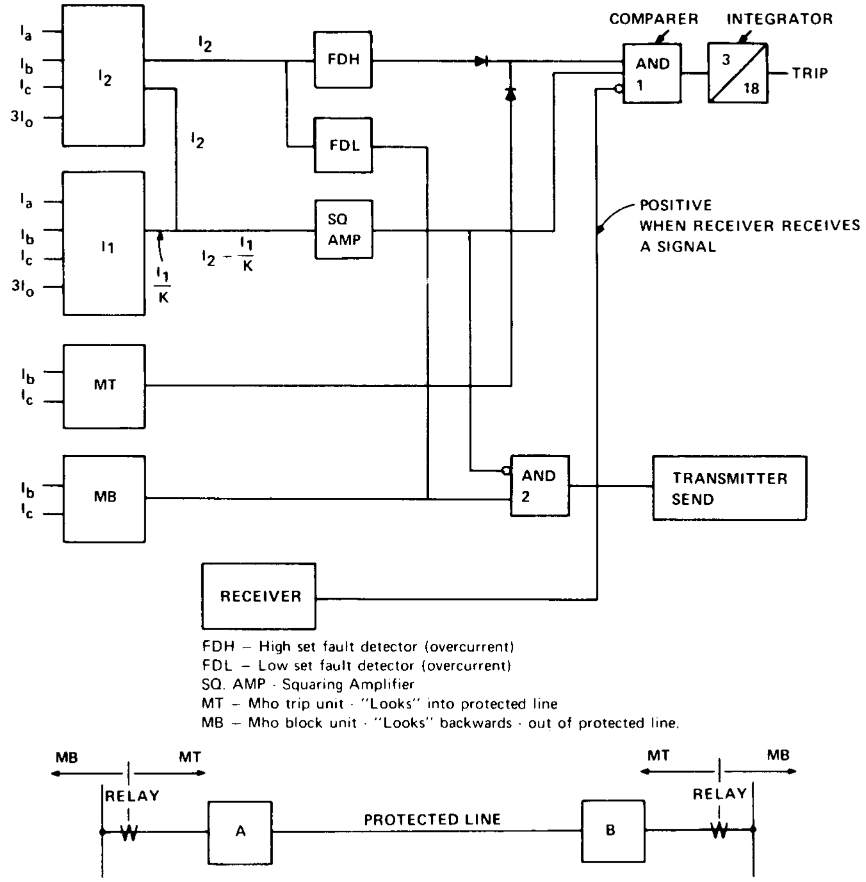
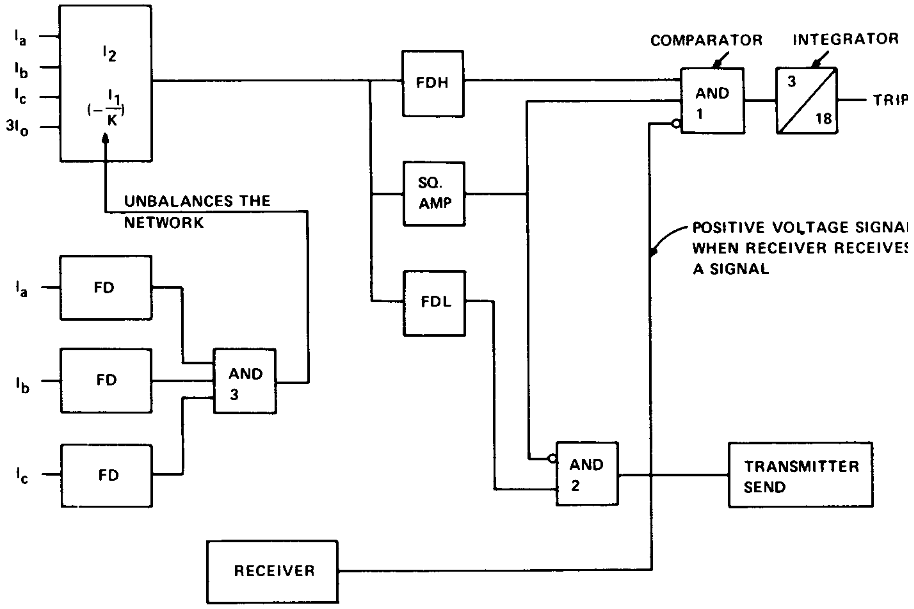
SEQUENCE MIXTURE	I_X	I_Y	ANGLE BETWEEN I_X AND I_Y
PURE I_1			120° (120°)
$I_1 + I_2$			85° (155°)
$I_1 + I_2 + I_0$			58° (180°)
$I_2 - \frac{I_1}{5}$			70° (35°)
$I_2 - I_0 - \frac{I_1}{5}$			168° (40°)

Figure 7. Vector Relationships In A Two-Terminal Faulted Line (Phase A–to–Ground)



FDH – High set fault detector (overcurrent)
FDL – Low set fault detector (overcurrent)
SQ. AMP - Squaring Amplifier
MT – Mho trip unit - "Looks" into protected line
MB – Mho block unit - "Looks" backwards - out of protected line.

Figure 8. Mho Supervised Phase Comparison Blocking Scheme



FDH – High set fault detector (overcurrent)
FDL – Low set fault detector (overcurrent)
SQ. AMP – Squaring Amplifier
FD – Individual phase fault detectors (overcurrent). All 3 operate for 3 phase fault.

Figure 9. Network Unbalancing Phase Comparison Blocking Scheme

(d) The MB function must be set to outreach all remote MT units.

(e) The phase angle difference between the $I_2 - I_1/K$ quantities obtained at all terminals of the protected line during all types of internal faults, and for any combination of phases must be less than 115 degrees.

Network Unbalancing Phase Comparison

Earlier in this section reference was made to schemes that employ pure negative sequence phase comparison except for the case of a three phase fault for which the sequence network is unbalanced to produce sensitivity to positive sequence currents. Figure 9 illustrates, in an abbreviated manner, the logic of such a blocking type of a scheme. It will be noted that unless all three of the FD units pick up, the phase comparison will be on a negative sequence basis. When all three FD units pick up, as they will for three phase faults, the network is unbalanced to produce an output for balanced positive sequence current inputs, and phase comparison takes place on a pure positive sequence basis. The FD units must be set to pick up above maximum full load current in order to insure pure negative sequence comparison on all but three-phase faults.

Since phase comparison is initiated by the same FDH for all kinds of faults, the ratio of positive sequence pick up to negative sequence pick up depends only on the amount of unbalance in the network introduced by FD operation. This is usually adjustable in the relay. In this kind of scheme FDH is set so that it picks up at a value of positive sequence current that is somewhat higher than the three phase fault current required to operate all three FD units. The response of FDH to negative sequence currents is then dependent on the network unbalance described above. FDL is set with a pick up that is below that of FDH.

With this kind of scheme, the requirements for satisfactory performance are given below:

(a) The FD function must be set with a pick up that is above full load current.

(b) The FDH function must be set to pick up, with the network unbalanced, at some level of positive sequence current that is higher than the FD pick up setting

(c) The FDL function must be set with a pick up below that of the remote FDH unit in order to maintain security during external faults.

(d) FD must pick up for all internal three phase faults.

(e) FDH must pick up for *all* internal faults.

Separate Positive & Negative Sequence Phase Comparison

The scheme described earlier in this section that is compromised of two separate phase comparison schemes may be represented in abbreviated logic by two diagrams similar to Figure 4. In one scheme the mixing network would be a pure negative sequence network. In the other scheme it would be a pure positive sequence network. In order for this approach to perform satisfactorily, the following requirements must be met.

(a) The negative sequence FDH must be set so that it operates for all unbalanced faults internal to the protected section.

(b) The negative sequence FDL must be set somewhat more sensitively than the remote FDH for security during external faults.

(c) The pick up of the positive sequence FDL must be set above full load to prevent continuous transmission under load.

(d) The pick up of the positive sequence FDH must be set somewhat higher than that of FDL at the remote end of the line for security during external faults.

(e) The positive sequence FDH must pick up for all three phase faults internal to the protected line section.

It should be recognized that this scheme will not detect three phase faults unless the fault current exceeds full load currents.

Summary of Phase Comparison Excitation Considerations

The following is a brief summation of the foregoing discussions.

1. There are a number of different ways in which phase comparison relaying may be arranged. However, in every case some combination or arrangement of positive and negative sequence components of current offers the best general approach.

2. Mixed excitation schemes are generally more difficult to apply than are schemes that compare pure sequence components.

3. Unless some sort of distance type fault detectors are applied, none of these schemes can detect three phase faults that produce currents that are below full load values.

In light of the above, the question of, "Why Phase Comparison?" might come to mind. Some of the answers are given below.

1. Phase comparison relaying is not affected by zero sequence mutual impedances that can cause directional type ground relays to misoperate.

2. Phase comparison relays with overcurrent fault detectors do not require a system potential supply in order to operate.

3. Phase comparison schemes are generally suitable for use on series compensated lines where distance type schemes may not be suitable.

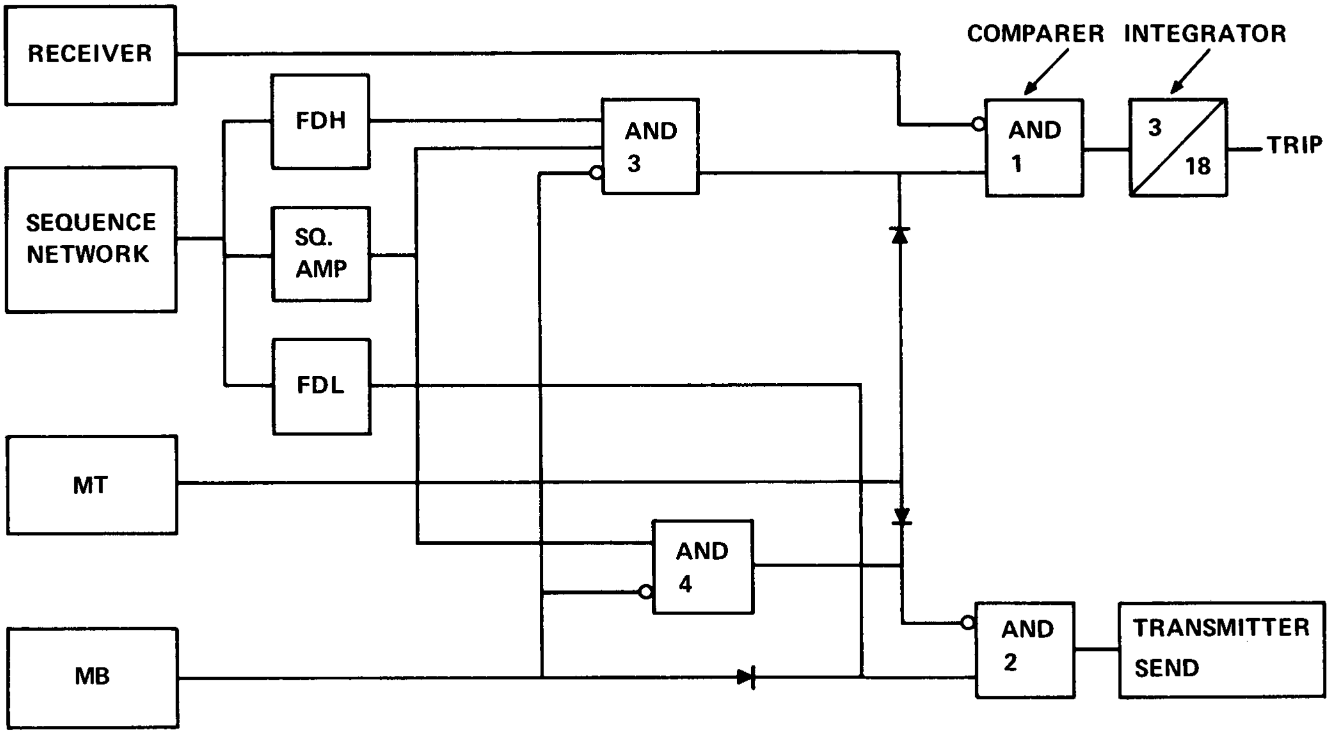
4. In their simple form, phase comparison schemes are relatively inexpensive.

5. Except for the mho supervised schemes phase comparison relays will not operate during system swings and out-of-step conditions.

COMBINING PHASE AND DIRECTIONAL COMPARISON

Since there is no single sequence component that could be used in phase comparison schemes to provide protection for all types of faults it is necessary to compensate for this deficiency. The previous section discusses means for mixing sequence components, unbalancing sequence networks for certain faults, and using two or more complete schemes each with different excitation. Another approach that is possible and that has gained acceptance is called "Combined Phase And Directional Comparison."

As the name implies, a combined phase and directional comparison scheme combines the principles of both phase comparison and directional comparison in one single scheme utilizing a common communication channel. The basic approach is to use pure negative or pure zero sequence for the phase comparison plus a set of mho functions at each end of the line for the directional comparison portion. One mho function (MT) operates for faults in the tripping direction. The other (MB) operates for faults in the blocking direction. Figure 10



FDH — High set fault detector (overcurrent)
FDL — Low set fault detector (overcurrent)
SQ. AMP — Squaring Amplifier
MT — Mho trip unit - "Looks" into protected line
MB — Mho block unit - "Looks" backwards - out of protected line

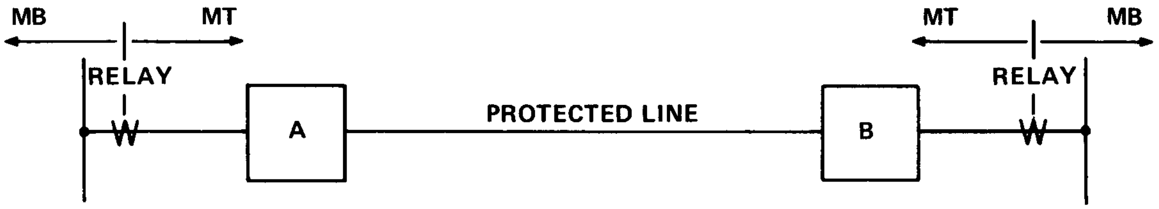


Figure 10. Combined Phase and Directional Comparison Blocking Scheme

illustrates the rudiments of a combined phase and directional comparison blocking scheme. Such a scheme is in general more sensitive than the schemes described earlier. This is so because the phase comparison, since it does not include positive sequence excitation, may be set to operate for low values of fault current. On the other hand the distance relays are basically able to discriminate between fault currents and load currents. Thus, the overall scheme will operate for fault currents well below full load current.

Referring to Figure 10 and assuming that the MT and MB functions do not exist, it will be observed that the scheme becomes the same as the simple phase comparison scheme of Figure 4. Thus, for any fault internal or external to the protected section for which no mho unit operates, the scheme will perform as a simple phase comparison scheme. On the other hand if it is assumed for the moment that the fault detectors and the squaring amplifier are inoperative, the scheme behaves as a simple directional comparison scheme under control of MT and MB. For an internal fault the MT units at both ends of the line operate to stop all transmission via AND2. At the same time they provide the lower input to AND1. With no receiver outputs, AND1 provides a signal to the associated integrator which after 3 milliseconds produces a trip output. For an external fault, say to the left of circuit breaker A, MB at A would operate to key the transmitter on. This results in continuous transmission of a blocking signal to the receiver at B. The output of the receiver at B blocks any MT operation at B from producing an AND1 output at that terminal. This in turn prevents any trip output from the integrator. At terminal A, since the fault is in the blocking direction, MT does not operate, the lower input to AND1 is not present, and no tripping can take place.

Since in the combined scheme it is possible, and even likely, that the mho functions, fault detectors, and squaring amplifier would all operate for some faults, it is necessary to set up an order of preference between the two modes of operation. For reasons that will be discussed subsequently, these combined schemes give preference to the directional comparison (mho functions) over the phase comparison (fault detectors), as may be observed from Figure 10. If an internal fault were to occur for which both modes functioned, the MT functions at both ends of the line would prevent any signal transmission by blocking AND2. This is true regardless of the attempt of FDL to start transmission. Also, the lower input to AND1 would be made continuously present by MT regardless of FDH and the squaring amplifier.

During an external fault to the left of terminal A for example, MB at that terminal will operate to key on the transmitter to send a continuous blocking signal to the remote end. At the same time MB will block AND4 from permitting the squaring amplifier from stopping carrier every other half cycle. This in turn will block tripping at terminal B. MB also blocks AND3 from allowing FDH to provide a comparer input. Thus, terminal A will not trip either.

The need for this directional comparison preference will become apparent if an external fault is considered to be just to the right of terminal B. Assume that for this fault both the phase comparison and the directional comparison detectors would operate. Thus, at terminal B the MB function will key its transmitter to send a continuous blocking signal. At terminal A the MT function will see the fault and attempt to trip but will be blocked by a continuously received blocking signal from the receiver. If the phase comparison squaring amplifier at B were permitted to key the transmitter off every other half cycle, the MT function at A would cause a trip during that half cycle. This is so because AND1 would produce alternate half cycle output pulses that would in turn time out the integrator. For this reason, and because it is likely that some external faults will result in the operation of both modes, directional comparison preference is employed.

Zero Sequence Excitation

As noted earlier, in combined phase and directional comparison schemes, the excitation could be pure zero or pure negative sequence current. Considering pure zero sequence excitation and referring to Figure 10, the sequence network would be a zero sequence network. Actually no network would be required in the relay for this case because the wye connected CT's normally used are in fact a zero sequence network in themselves. With zero sequence excitation the phase comparison portion of the overall scheme would not be capable of operating for phase-to-phase and three-phase faults. For this reason the directional comparison portion must include MT and MB functions that can detect and operate for faults involving any two or more phases. This requires that the MT and MB functions each be three single phase mho units.

It should be noted that distance relays designed to operate for faults involving two or more phases will operate for double-phase-to-ground faults and also for certain close-in single-phase-to-ground faults. Thus, it is reasonable to expect that both the phase and directional comparison modes will be activated for many faults and so the preference is required.

In order to obtain satisfactory performance from such a scheme, the following requirements must be met:

(a) The FDH function must be set so that it operates for all single-phase-to-ground faults internal to the protected line.

(b) The FDL function must be set somewhat more sensitively than the remote FDH for security during external faults.

(c) The MT function must be set with a reach that is long enough to enable it to see all multi-phase faults on the protected line.

(d) The MB function must be set to reach further than the remote MT unit for security during external faults.

(e) The MB function must not operate for any *internal* single-phase-to-ground fault for which the associated MT function does not operate otherwise tripping will be blocked.

Negative Sequence Excitation

The logic shown in Figure 10 will apply as well to negative sequence phase comparison excitation as it does to zero sequence excitation. In this case, however, the sequence network illustrated would have to be a negative sequence rather than a zero sequence network. Also, since the negative sequence phase comparison will protect against all unbalanced faults, the MT and MB (directional comparison) functions are required only for three-phase fault protection. However, if these functions are designed to respond to all multi phase faults, then phase-to-phase and double phase-to-ground faults will be protected by both modes while single-phase-to-ground faults will be protected by only the phase comparison mode, and three phase faults by only the directional comparison mode.

In order to obtain satisfactory performance from such a scheme, the following requirements must be met.

(a) The FDH function must be set so that it operates for all unbalanced faults internal to the protected line.

(b) The FDL function must be set somewhat more sensitively than the remote FDH for security during external faults.

(c) The MB function must be set to reach further than the remote MT unit for security during external faults.

(d) The MT function must be set with a reach that is long enough to enable it to see all multi-phase faults on the protected line.

(e) The MB function must not operate for any *internal* fault for which the associated MT function does not operate otherwise tripping will be blocked.

Summation of Combined Phase & Directional Comparison Considerations

1. Both the zero and the negative sequence schemes require the use of directional distance measuring functions. Thus, both schemes require potential supplies, and both schemes are sensitive to system swings and out-of-step conditions.

2. The scheme using zero sequence excitation requires mho functions that must operate for all multi-phase faults with the possible exception of double-phase-to-ground faults.

3. The scheme using negative sequence excitation requires mho functions that respond to three phase faults only.

4. Both schemes require that the MB functions do not operate for any *internal* faults for which the associated MT functions do not operate. Since phase distance mho relays can respond to single-phase-to-ground faults and faults on adjacent phases, the selection of the type of mho functions employed for any given application requires consideration. The factors involved in this consideration are outside the scope of this discussion.

5. Neither scheme will misoperate as a result of zero sequence mutual coupling between the protected line and other parallel lines.

6. In general both schemes will have the same sensitivity. That is, the $3I_0$ sensitivity of the fault detectors in the zero sequence scheme will be about the same as the I_2 sensitivity of the fault detectors in the negative sequence scheme. For some long lines with strong ground sources, the distribution of fault currents may be such that for faults near one terminal the I_2 at the remote terminal is greater than $3I_0$ at the same terminal. For such applications the negative sequence scheme may be best.

7. Both schemes will operate for three phase faults that produce currents well below full load values.

8. These schemes are a half way point between pure phase comparison and pure directional comparison. As such they require coordination between the two modes of operation as noted in item (4) above. This problem is not present in the pure schemes.

BLOCKING vs. TRIPPING SCHEMES

Earlier discussion in conjunction with figure 2 provides a basis for further consideration of blocking vs tripping pilot schemes. Figure 2C illustrates the comparer-integrator logic for a tripping scheme using an ON-OFF type of pilot channel. In order to trip, a receiver output is required to be present during the half cycle that the local current is positive. Figure 2D is representative of a blocking pilot scheme where tripping will take place if there is no receiver output during the half cycle that the local current is positive.

If we consider that an input to, or an output from a logic box is a positive going signal, the logic illustrated in Figures 2B and 2C assume that a received signal at the input of a receiver will produce a positive going voltage signal at the output of the receiver to the relay logic. This is not always true. Some types of receivers will produce negative (or reference) voltage outputs when a signal is present at the input, and a positive signal output when nothing is received. If this were the situation in Figure 2, Figure 2C would then represent a blocking scheme while Figure 2D would be a tripping scheme. In some applications where receiver outputs are inverted, the interface between the receiver and the relay logic includes an invertor (INV) which in effect inverts the receiver output signal so that a received signal produces a positive going signal at the output of the invertor. The same general statements regarding signal polarities applies to the keying requirements for transmitters. Some transmitters may require a positive signal while others a reference or negative signal to key them off of their quiescent states.

The main point to be gained from the foregoing discussion is that it is not always possible to determine from a logic diagram whether a scheme is of the blocking or tripping type unless an indication is given as to the receiver output voltages. This applies to frequency shift as well as ON-OFF communication equipment.

It will become apparent from subsequent discussion that it is extremely difficult, if not impossible, to provide a concise rigorous definition of the terms Blocking Scheme and Tripping Scheme. Possibly it would be well to proceed with a discussion of the different kinds of channels, their characteristics, and their application before attempting a definition.

Type of Channels

The total channel is composed of the communication equipment itself plus the path or link over which the signal is sent. For relaying purposes there are two basic types of communication equipment.

1. ON-OFF

2. Frequency-shift

The ON-OFF type, as the name implies, operates with the transmitter either being keyed on or off by the relay logic. That is, the transmitter at any given instant is either sending an unmodulated signal or it is sending nothing.

There are two kinds of frequency-shift equipments. The most prevalent is the two-frequency kind. With this type, the transmitter can send either of two closely spaced frequencies. When no keying signal is applied to the transmitter it sends one of these two frequencies. When the transmitter is keyed, it shifts to the other frequency. It is always sending one or the other. The frequency-shift receiver has two separate outputs one for each of the two transmitted signal frequencies. Thus, if the transmitter is sending the MARK frequency the MARK output is present in the receiver. If the transmitter is sending the SPACE frequency, the receiver SPACE output is present. These types of receivers are basically FM receivers and utilize discriminators. Because of this the SPACE and MARK outputs from the receiver cannot both be present simultaneously. Also, broad band noise at the input to the receiver tends to provide a balanced signal to the discriminator which forces its output toward zero. If the noise is severe enough to swamp out the real signal it can cause random receiver output or all output to disappear.

The other kind of frequency-shift equipment is a three-frequency type. When this type of transmitter is in its quiescent state it sends the center frequency. It has two separate keying inputs so that it can be keyed to shift high or low (MARK or SPACE) from the center frequency. The three-frequency receiver receives all three frequencies but provides only two outputs to the relay logic, the high shift and low shift outputs. When the receiver receives the center frequency neither the high nor low outputs are present. Here again the MARK and SPACE outputs (high and low) cannot both be present simultaneously, and severe broad band noise at the receiver inputs can result in receiver output.

There are several characteristics of communication equipment directly related to phase comparison relaying performance that might well be discussed. Phase comparison types of schemes compare the phase angle of a current derived at one end of a line with a communication signal received from the remote end. The communication signal arrives in a MARK-SPACE arrangement that should represent the positive and negative half cycles of current at the transmitted end of the line. Actually this is not possible for several reasons.

1. There is a time lag from the instant a transmitter is keyed until the output reflects a change. This build up is generally a very short time and is usually insignificant.

2. There is the propagation time from the instant the transmitter sends until this signal arrives at the remote location, approximately 1 millisecond for every 180 miles of distance. The same applies from the instant the transmitter stops until the remote signal is gone.

3. There is the build up time in the receiver from the instant the signal appears at its input until the output reflects the change of state. This time plus the build up time in the transmitter is called the channel operating time.

4. There is the tail off time in the transmitter from the instant the keying is removed until the output signal changes or disappears. This is generally very short and is usually insignificant.

5. There is the tail off time in the receiver from the instant the input changes until the output changes accordingly. This time plus the tail off time of the transmitter is called the channel release time.

6. In ON-OFF channels the operating and release times are not generally the same. They can vary with frequency and attenuation.

7. In frequency-shift channels the discriminator employed in the receiver can be balanced so that build up and tail off times are equal, or it can be unbalanced (biased) to the MARK or SPACE side. For example, if it is biased toward MARK and the input signal is symmetrical (half cycle MARK and half cycle SPACE), the output will be more than a half cycle MARK and less than a half cycle SPACE.

8. In general wide band channels tend to operate and release faster than narrow band channels. That is, faster channels use more spectrum than slower channels.

It is obvious from the foregoing that the received signal at any given terminal is not an exact analog of the remote current. There are techniques used in phase comparison schemes to compensate for this and they will be discussed subsequently. Until then it should be assumed that the received signal provides a true representation of the phase position of the remote current.

Types of Communication Links

The communication link over which the transmitted signal is propagated to the remote receiver can take several forms. These are noted below.

1. Directly over the power line (Power line carrier)

2. Multiplexed over the power line (Single Side Band Carrier)

3. Multiplexed over microwave (Microwave)

4. Pair of Wires (Pilot Wire)

5. Leased Facilities (Telephone Company)
    (a) Metallic pilot wire
    (b) Microwave
    (c) Cable

A distinction is made between leased facilities and the other (power company owned) facilities because in many cases the telephone company defines the characteristics of the channel without defining the type of link.

The ON-OFF type of communication equipment is used exclusively over power line carrier links. The transmitted signal is propagated along the power line between the transmitter and the remote receiver. These equipments usually operate in the frequency range of 30-200 kHz.

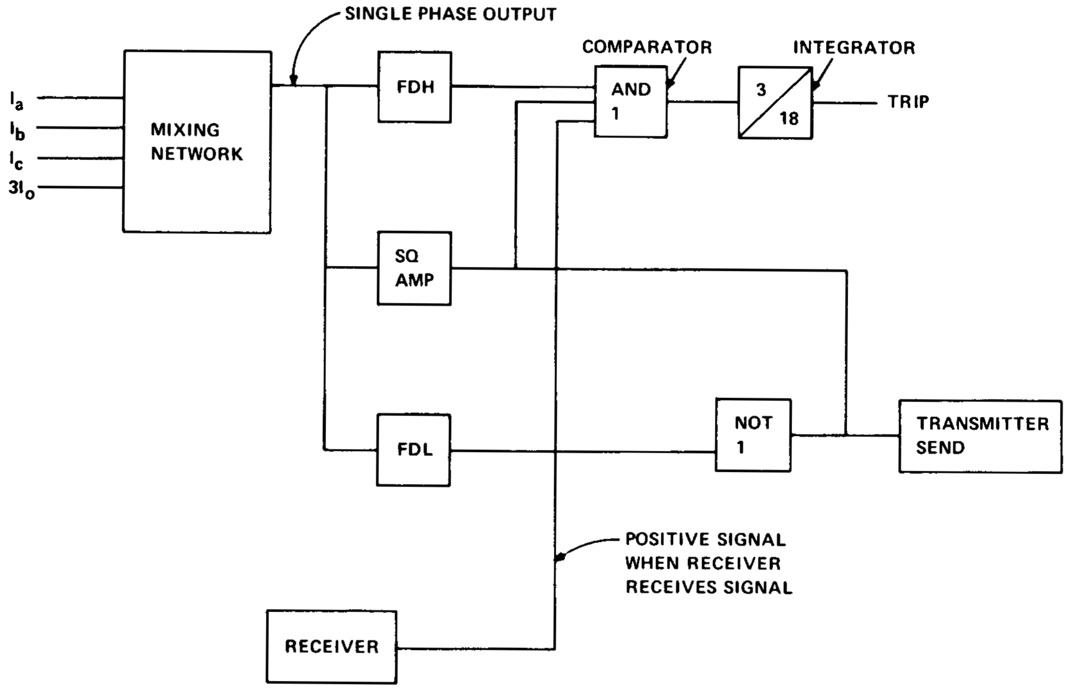
The frequency-shift equipments are available in several frequency ranges. First there are those in the audio range. These are generally employed over single side-band, microwave, pilot wires, and leased facilities. There are also frequency shift channels in the power line carrier frequency range. These are employed directly over the power line as are the ON-OFF types of equipment. Finally there are the frequency shift equipments that operate in and occasionally outside the power line carrier spectrum. These are employed over microwave and leased facilities.

Power Line Carrier Links

It is obvious that the performance of any channel that utilizes the protected power line itself as a link will be affected in some way by faults on the power line. A fault on a transmission line can attenuate or completely block a signal, transmitted at one end of the line, from being received at the remote end. Faults external to the protected line have no effect on the signal attenuation since transmission lines that incorporate power line carrier channels are trapped at each end (See Figure 11).

In the case of ON-OFF power line carrier channels, the operating frequencies of the equipment at all terminals of the protected line are generally the same. Thus, a signal transmitted from any terminal is received at all terminals. This is not a necessary requirement for using this kind of equipment. Rather it is desirable because the protection schemes that use ON-OFF channels can accommodate a single frequency arrangement and this conserves the carrier spectrum.

When frequency-shift equipment is used over power line carrier, the frequencies of each transmitter on the line must be different from all the others on the same line. For example, if the communication equipment in Figure 11 is of the frequency-shift type, the transmitter at the left end must operate at the same frequencies as the receiver at the right end. Also, the right end transmitter and left end receiver must operate at the same frequencies while the frequencies of the two transmitters must be different. This is necessary because with frequency-shift equipment the transmitters associated with a given line protection scheme are not all generally sending the MARK or the SPACE frequencies at the same time. Thus, if a receiver were able to receive more than one transmitter, it could be simultaneously receiving a MARK



FDH – High set fault detector (overcurrent)
FDL – Low set fault detector (overcurrent)
SQ. AMP – Squaring Amplifier

FDH provides a continuous output when the single phase current output from the mixing network exceeds the pick-up setting.

FDL provides a continuous output when the single phase current output from the mixing network exceeds the pick-up setting.

SQ. AMP provides an output only on the positive half cycle.

Note: This sceme requires transmitters of different frequencies at each line terminal so that a receiver cannot receive the locally transmitted signal.

Figure 11. Typical Power Line Carrier Arrangement

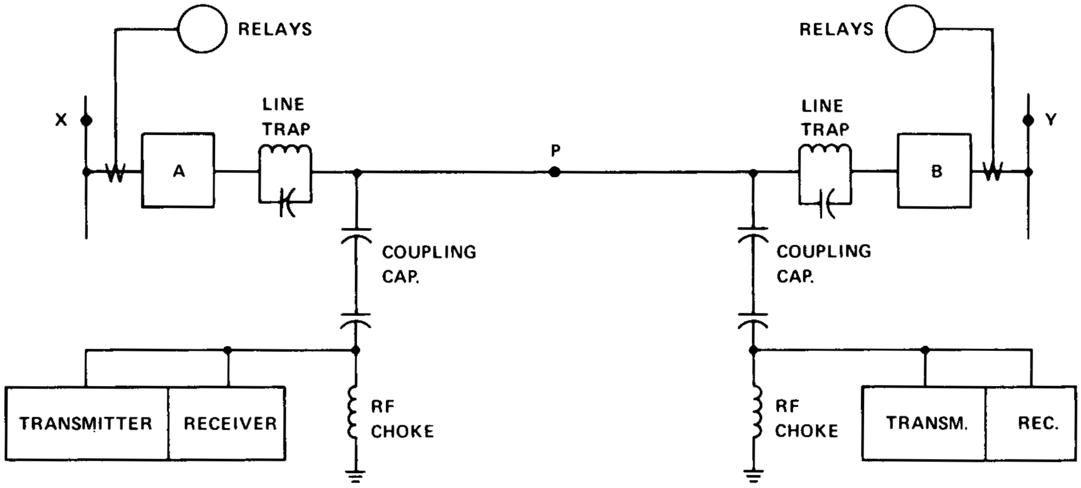


Figure 12. Single Phase-Comparison Tripping Scheme

signal from one and a SPACE signal from another. This would not result in a workable protection scheme.

When power line carrier channels are used, significant losses are present in the coupling equipment and the line itself. Depending on these losses and the ambient noise on the line, the transmitter power required may vary from about 1 Watt to 10 Watts and even more in extreme cases.

Consider an ON-OFF tripping type of scheme as defined by Figure 12. For a moment assume that FDL and NOT1 do not exist in the logic. During an internal fault, the currents out of the mixing (or sequence) networks at both ends of the line are in phase with each other so that the outputs of the SQ AMP are in phase at both ends of the line. The transmitters at both ends of the line are keyed on during the same half cycles that their associated SQ AMP's are attempting to trip via AND1. Thus, the receivers will be supplying the bottom input to AND1, and tripping will take place when FDH operates to provide the third input.

For external faults, the currents out of the mixing networks at the two ends of the line will be 180 degrees out of phase with each other. Therefore, during the half cycle that the SQ AMP at one end of the line is producing an output, the one at the remote end is not, so no tripping will take place. It should be noted that a tripping type of scheme over an ON-OFF channel requires transmitters of different frequency at each end of the line so that no receiver can receive the locally-transmitted signals; otherwise tripping would occur during external faults. For this reason, such schemes are not generally applied.

It appears that the tripping scheme as described above has no need for an FDL function since no blocking coordination is required as is in a blocking scheme. However, this is not the case. The FDL and NOT1 functions provide a means for tripping when one end of the line is open as when picking up a faulted line from one end. For such a condition, the SQ AMP at the open end receives no current and so produces no output to key its transmitter. Without a received signal the closed end of the line cannot trip under any conditions even in the presence of a fault. The FDL function acts as a current detector. It is set with a very very low pick up so that any significant output from the mixing network causes it to produce a continuous output. When the mixing network outputs goes to zero, FDL drops out causing an output from NOT1 which in turn keys the transmitter on continuously. This is received at the remote end to provide a continuous signal at the bottom input to AND1. Any fault that picks up FDH will then be tripped at the closed end of the line.

If the mixing network includes a positive sequence output, load current will keep FDL picked up continuously. If the mixing network includes only zero and/or negative sequence outputs, load current will not keep FDL picked up. Thus, with zero or negative sequence phase comparison the receivers at both ends of the line will be producing outputs to AND1 continuously. When a fault occurs, FDL picks-up very fast to restore the keying function to SQ AMP. This operation resembles a blocking scheme, although it is often called a permissive tripping scheme.

Another scheme to facilitate tripping on single end feed uses a circuit breaker 52/b switch rather than FDL and NOT1. When the breaker is open, the 52/b switch closes and keys the associated transmitter on continuously. When the breaker is closed, the 52/b switch is open and keying is under control of the SQ AMP. While on the surface the use of 52/b appears simple and direct, the following problems arise that can require more complex logic and station wiring:

1. The 52/b contacts do not generally operate in synchronism with the main poles of the breaker so some timing functions must be included with the logic to compensate for this.

2. In multi-breaker schemes, such as ring buses, two breakers at each terminal are associated with each line so 52/b switches from each breaker are required in series.

3. In multi-breaker schemes one of the two breakers may be out of service but in the closed position. This would require a bypass of its 52/b switch which is open.

Regardless of which tripping scheme is used, it is obvious from Figure 11 that in order to trip either circuit breaker A or B for an internal fault at P it is necessary to get a carrier signal through the fault. If the fault attenuates the signal so that this does not happen, no tripping can take place. The amount of attenuation in signal that is produced by the fault will depend on the type of coupling (single phase, interphase, etc.), the type of fault, the phase involved, and the location of the fault on the line. The evaluation of these factors is outside the scope of this discussion.

Figure 13 illustrates the same tripping scheme as Figure 12 except that it utilizes a frequency shift rather than an ON-OFF communication set. The same comments apply to this scheme as do to that of Figure 12.

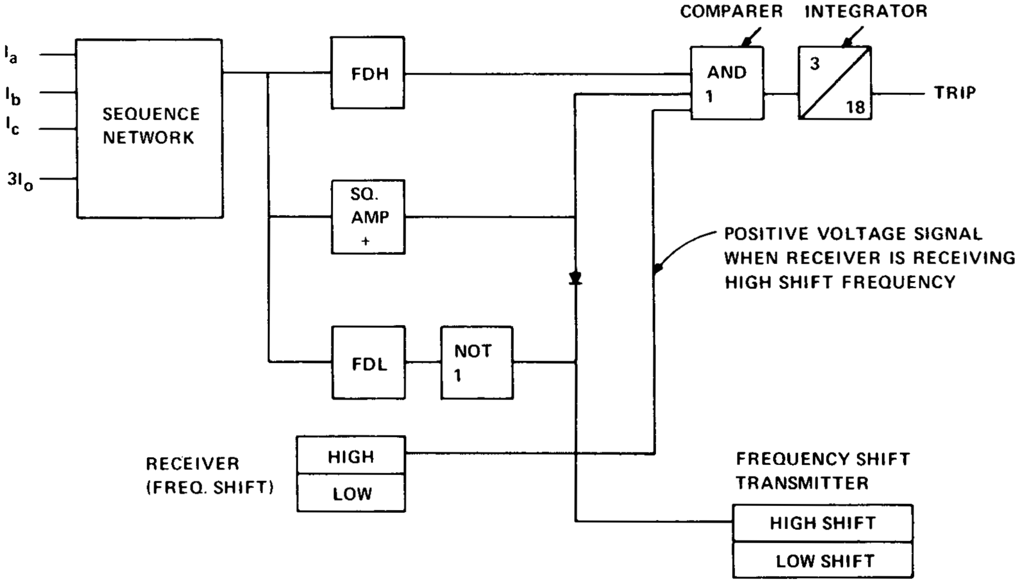
A tripping scheme that operates over a power line carrier channel runs the risk of a failure to trip on internal faults because of signal attenuation. During external faults the line traps isolate the signal on the protected line from the fault. This is of no significance because attenuation or loss of signal on external faults cannot result in any misoperations. Conversely, a blocking scheme is unaffected by loss or attenuation of signal during internal faults because absence of a signal is required in order to trip. During external faults it is important that the blocking signal be isolated from the fault because loss of the signal can result in a false trip. The line traps provide this isolation.

Figures 4 and 14 illustrate phase comparison blocking schemes with ON-OFF and frequency-shift channels respectively. Figure 4 was discussed earlier and Figure 14 is exactly the same except for the high frequency shift which is not used in the protection scheme. While only one of the two frequencies of the frequency-shift equipment is used in the protection scheme, the second frequency does perform a useful function. It provides a means for continuous monitoring of the channel. Since one of the two frequencies is always being transmitted, it is possible to monitor the signal at each receiver continuously and incapacitate the protective scheme and/or provide indication at that terminal if the signal is lost.

Most schemes that use an ON-OFF channel are arranged so that no transmission takes place during normal conditions (no fault). This does not lend itself to continuous monitoring. However, schemes are available that periodically start transmission of a signal at one end of a line which, when received at the remote end, initiates a return transmitted signal. Such schemes can be started manually or automatically on a time schedule. They are called carrier check-back schemes. They can be arranged so as not to affect the normal operation of the scheme even in the event of a fault during a check-back operation.

For the most part, phase comparison blocking carrier schemes use ON-OFF rather than frequency-shift channels, possibly for one or more of the following reasons:

1. The overall speed of the protective scheme is directly related to the speed of the channel.



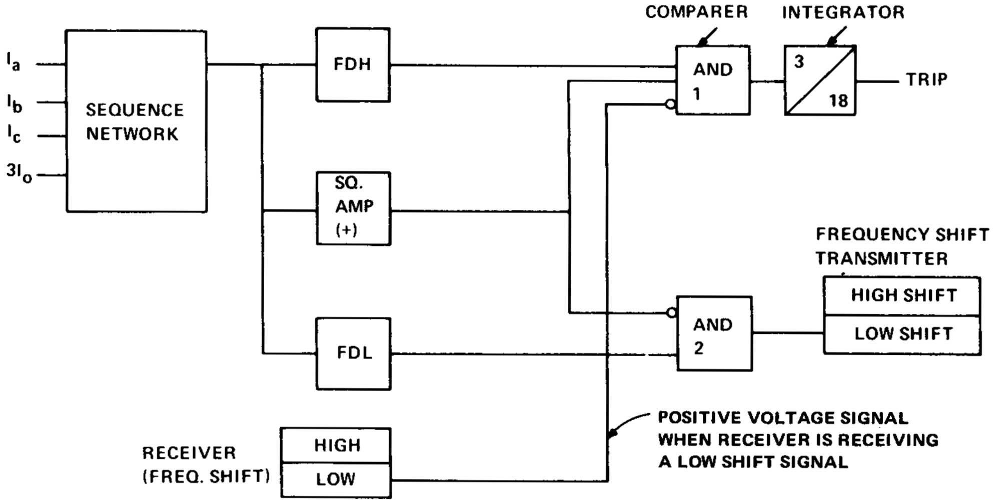
FDH – High Set fault detector (overcurrent)
FDL – Low Set fault detector (overcurrent)
SQ. AMP – Squaring Amplifier

FDH provides continuous output when the sequence network output exceeds the pick-up setting.

FDL provides a continuous output when the sequence network output exceeds the pick-up setting.

SQ. AMP provides an output only on the positive half cycle.

Figure 13. Single Phase-Comparison Tripping Scheme



FDH – High Set fault detector (overcurrent)
FDL – Low Set fault detector (overcurrent)
SQ. AMP – Squaring Amplifier

FDH provides continuous output when the sequence network output exceeds the pick-up setting.

FDL provides continuous output when the sequence network output exceeds the pick-up setting.

SQ. AMP provides an output only on the positive half cycle.

Figure 14. Single Phase-Comparison Blocking Scheme

Until recently high speed frequency shift carrier channels were not available. Even today the ON-OFF channel is somewhat faster than the fastest frequency-shift channel.

2. Noise at the input of an ON-OFF channel receiver would tend to produce a blocking signal output. Noise at the input of a frequency-shift channel tends to drive its output to zero which is a tripping condition (in a blocking scheme). This tends to make the frequency-shift blocking scheme less secure against false tripping during external faults. It is possible to build channel condition detectors (signal to noise, loss of channel, etc.) into frequency-shift channels and block tripping when these detectors indicate trouble, but these features increase the complexity and the cost. This approach tends to make the blocking scheme resemble the tripping scheme since the receiver must now indicate an intact channel in order to trip.

3. Aside from the ability to accommodate continuous monitoring, the frequency-shift channel provides little advantage over the ON-OFF carrier channel.

There are very few if any phase comparison tripping schemes in service over carrier channels mainly because of the fear that it will not always be possible to get a trip signal through a fault.

There is another type of scheme that has recently been gaining some favor. This is called Unblocking. It is a cross between blocking and tripping in that it operates in the blocking mode but the blocking signal is sent continuously even in the quiescent state (no fault), and so it must be turned off in order to trip. Thus this scheme, as in the tripping schemes previously described, must include some means to stop the blocking signal from being transmitted at an open terminal in order to permit tripping of the closed remote terminal in the event of a fault. Here again the FDL logic of Figure 12 and 13 or the circuit breaker auxiliary 52/b switch could be used.

In general, unblocking utilizes frequency-shift channels because this permits monitoring of the continuous blocking signals. As they are usually applied, ON-OFF channels do not lend themselves to monitoring because the single frequency system transmits the same frequency from all transmitters and the loss of any one transmitter could not be detected. If applied in a normal duplex frequency basis (one in each direction) the ON-OFF channel would provide the monitoring features at the cost of carrier spectrum. However, this disadvantage can be overcome by the use of a new application of ON-OFF equipment where the transmitters at the different terminals are operating at frequencies offset from each other yet close enough to be nominally a single frequency system. This application permits monitoring, and at the same time has the advantage of a higher channel speed than the frequency-shift channels, while utilizing less channel spectrum in three terminal line applications.

Single Side Band Carrier Links

Like the carrier channels discussed above, the single side band communication equipment is coupled directly to the power line through coupling capacitors and utilizes the power line to propagate the signal. In general, the output frequency of the single side band equipment is in the 30-200KC carrier spectrum, while the multiplexed channels are of the frequency-shift type that operate in the audio range. The only advantage of this type of arrangement is that it provides a multi-channel equipment over a minimum of channel spectrum with a cost economy over single channels.

Single side band carrier links have not been used extensively in this country for protective relaying. When they are used for this purpose they usually include a relatively high speed frequency-shift channel for the relaying function plus a limited number of narrow band equipments for control functions. On some occasions a high speed ON-OFF channel has been multiplexed over single side band. These high speed channels usually operate in the kilohertz range, and because of the speed requirement are of the wide band variety.

The final R.F. amplifier of the single side band transmitter has, by design, a certain maximum power capability. Each of the signals that is multiplexed over this equipment uses a fraction of that total power depending on the percent modulation as indicated by the following equation.

$$P_n = P_t \left(\frac{M}{100}\right)^2$$

where:

P_t = total capability of the output amplifier
P_n = Power output of a given multiplexed signal
M = Percent modulation by the given multiplexed signal

It should be noted that the total percent modulation for all multiplexed signals must not exceed 100 percent. Thus, if only two signals are multiplexed, each at 50 percent modulation, each signal will have one fourth the total power. For four signals equally muitiplexed only one sixteenth the total power will be available to each. When relaying is used in conjunction with voice and control functions on single side band it is often necessary to exhalt the relaying channel signal when it is called on to block or trip. This results in the particular signal temporarily usurping most, if not all, of the total available power at the expense of the other functions.

Phase comparison relaying has been employed over single side band links. In general, the high speed frequency-shift type of channel is used in a tripping scheme, and the ON-OFF type in a blocking scheme. The same basic comments apply to these schemes as were made above for similar carrier schemes applied without the single side band. The single side band equipment adds nothing to the overall performance of the protective relay scheme except that it contributes to better spectrum utilization and is economically advantageous to use when there are several voice and control functions in addition to relaying required between the same terminal points.

Microwave Links

Microwave links are quite commonly used for protective relaying including phase comparison schemes. However, because of the high cost of the microwave equipment, the applications are generally limited to cases where a large number of control and/or monitoring functions are needed between the same terminals as the relaying.

Since microwave links propagate through the atmosphere, rather than over the power line, they are generally unaffected by faults and noise on the power system. Thus, with a microwave link there is no problem of getting a signal through the fault, so tripping type schemes are very acceptable. On the other hand, since there is a possibility of fading of the microwave signal, there is some reluctance to use it in blocking schemes for fear of false tripping in the event of a fade during a nearby external fault. However, blocking schemes are used occasionally mainly because the tripping scheme requires special circuitry (as described earlier) in order to trip on single-end feed to a fault.

The communication equipment multiplexed on to a microwave system for protective relaying is invariably of the frequency-shift type, and usually of the high speed variety. Figures 13 and 14 are representative of the tripping and blocking schemes respectively. Since, as mentioned above, the microwave signal can fade, some of the frequency-shift receiver equipments include channel status detectors that operate into the relay logic to incapacitate all tripping when the channel conditions are not normal. The ability to trip is then automatically reinstated when normality returns. With such an arrangement, complete loss of receiver output would incapacitate tripping. If the scheme were a blocking scheme similar to that of Figure 14, complete loss of channel during an external fault would permit a false trip unless an incapacitating feature were included in the scheme.

The receiver has only two outputs (high and low). Since the scheme trips on internal faults during the absence of the low-shift output, and since the absence of both the low and high shift outputs incapacitates tripping (where used), the implied requirement for tripping is the presence of the high-shift receiver output. While such a scheme is called a blocking scheme it appears to be, at least by implication, a tripping scheme.

In any case, there is nothing about a microwave channel to alter the previous discussion concerning phase comparison protection. The same basic schemes may be used with the understanding that the microwave signal can fade on occasion. For the most part, phase comparison relaying schemes over microwave channels have been of the tripping types.

Pilot Wire Links

There are very few, if any, privately owned pilot wires in this country that are used as a link in phase comparison schemes. However, such applications would require a frequency-shift communication equipment used in either a tripping or blocking mode as indicated in Figures 13 and 14 respectively. Aside from the considerations involved in tripping for a fault with single-end feed, which were discussed previously, the selection between a blocking and a tripping scheme will generally result from a compromise between security and reliability. In order to make such a selection, consideration of the pilot pair, its protection, and its physical location in relation to power conductors must be evaluated.

In general, a high speed channel would require pilot wires that have a frequency response that is somewhat better than the standard telephone voice circuits.

Possibly because of the uncertainties of channel characteristics, plus the availability of pilot wire relays that are much lower in overall cost, phase comparison over privately owned pilot wires is not a common application.

Leased (Telephone Company) Facilities

There has been some use of phase comparison relaying over leased facilities including voice grade pilot wire circuits. In general, if a customer requires or specifies the characteristics of a leased channel, the local telephone company could provide this link over microwave, cable, even pilot wires, or a combination of these. In such cases the selection between tripping and blocking schemes will depend on the performance of the channel as specified. The same basic schemes of Figures 13 and 14 would apply.

Summation of Blocking vs. Tripping Schemes

The foregoing discussion of blocking and tripping schemes was presented without the benefit of a concise definition of these terms. As indicated in the discussion, the difficulty of making such definitions which would always apply is brought about by the channel status feature used in some frequency-shift blocking schemes. Such arrangements tend to be hybrids. Thus, the following simple definitions exclude any considerations of channel status features:

- A blocking scheme is one that requires a specific output signal from the associated receiver in order to block tripping. Tripping can only take place during the time that this signal is absent.
- A tripping scheme is one that requires a specific output signal from the associated receiver in order to permit tripping. Tripping can only take place during the time that this signal is present.
- Where channel status logic is used, these definitions will have to be modified to meet the exact logic of the scheme.

In general, the selection of a blocking or a tripping scheme is one that should be made in conjunction with the chosen channel and with a knowledge of the channel characteristics in the face of system noise. Many different combinations are possible, but of these, only a selected few will meet any given set of requirements.

SINGLE vs. DUAL PHASE-COMPARISON

In all the phase-comparison schemes described so far, a trip attempt is made only every other half cycle. In the examples illustrated, this was every positive half cycle. Such schemes are termed single phase-comparison as against dual phase-comparison where a trip attempt is made every half cycle, positive and negative.

The only advantage of dual-comparison is that its maximum operating time to trip on internal faults will be a half cycle faster than the maximum time for the single phase-comparison. The minimum times for both schemes will be the same. This difference in maximum time results because a fault could occur at such an instant in time when the current is just going negative. Under such conditions, the single phase-comparison would have to wait till the next positive half cycle while the dual phase-comparison could trip on the upcoming negative half cycle.

While, as a general rule, high speed operation and security are on opposite sides of the coin, it is possible to design dual phase-comparison schemes that can provide the added speed with little or no loss in security. However, these schemes are somewhat more complex than equivalent single phase-comparison schemes. Figure 15 illustrates the dual phase-comparison tripping scheme that is the counterpart of the single phase-comparison scheme of Figure 13. The differences are noted below:

1. The dual scheme uses two separate comparer-integrator combinations, one for the positive half cycle and the other for the negative half cycle.
2. A three-frequency, frequency-shift channel is used in dual phase comparison. The high-shift operates in conjunction with the positive half cycle while the low-shift works with the negative half cycle. When the channel is not keyed to either high or low, it operates on the center frequency. There is no center frequency output from the receiver into the relay tripping logic.
3. AND3 is included to make it impossible to key both frequencies simultaneously. It also gives preference to the low-shift which is sent continuously when FDL is dropped out. Thus, on single-end feed tripping can take place only on the negative half cycle.

The center frequency, while not actually used in the relay tripping logic, adds security to the scheme during transient conditions.

The dual phase-comparison scheme of Figure 15 could be modified to operate over a two-frequency, frequency-shift channel by eliminating AND3, FDL, NOT1, and the center frequency. The transmitter could then be arranged to send the low-shift frequency continuously except when keyed by the positive SQ. AMP to the high shift frequency. This arrangement, though simpler than the three-frequency scheme, is deemed to be less secure.

Figure 16 illustrates a dual phase-comparison blocking scheme using a two-frequency, frequency-shift channel. Since one or the other of the two frequencies must be on at all times, and since both are blocking frequencies, there appears to be little need for an FDL function. Thus, it is not included. When the transmitter is not keyed, it sends low-shift continuously and when it is keyed by the negative squaring amplifier, it shifts to high for the negative half cycle. This scheme is simpler than that of Figure 15 but probably is not as secure.

There does not appear to be any good purpose for a three-frequency channel in dual phase-comparison blocking schemes since the center frequency would not add to the security, or otherwise improve the performance.

It is interesting to note that a dual phase-comparison scheme using an ON-OFF channel would have to be a combined blocking and tripping scheme. During one polarity of half cycle, it would have to trip on absence of any received signal (blocking), and on the other polarity of half cycle, it would have to trip in the presence of the received signal.

In general, it may be concluded that dual phase-comparison may be accomplished in the blocking and in the tripping modes. The overall performance of the scheme will be dependent on the characteristics of the channel selected. While dual phase-comparison will reduce the maximum tripping time, it does so at the expense of simplicity and possibly some security depending on how it is accomplished.

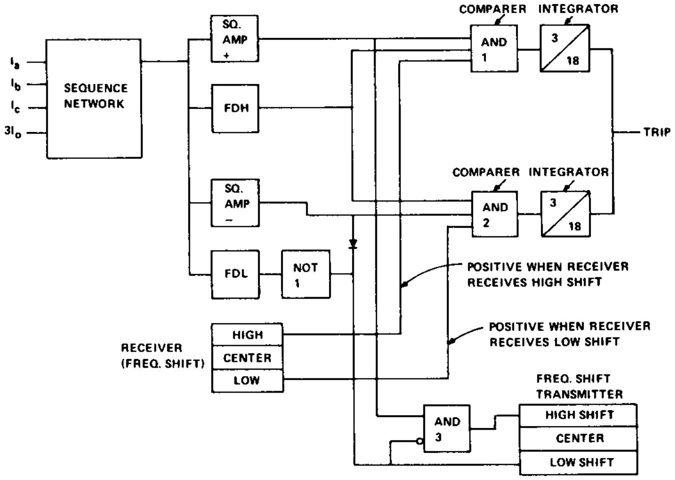
REFINEMENTS TO BASIC SCHEMES

There are a number of standard refinements that are required and normally included in all phase comparison schemes. These will be discussed in terms of the basic blocking scheme of Figure 4, but will apply generally to all schemes, sometimes in a somewhat different form.

SYMMETRY ADJUSTMENT

As was noted in a previous section, receivers are not always symmetrical in their response. That is, if a transmitter is keyed on and off symmetrically every half cycle, the remote receiver output would not necessarily correspond exactly to the keying signal. For example, if an ON-OFF transmitter were keyed on for a half cycle and then off for a half cycle, and so on, the remote receiver output might be on for more than a half cycle and off for less than a half cycle. This effect is primarily due to the filter response in the receiver and is common with ON-OFF type of equipment. It is not a constant value but rather depends on operating frequencies as well as received signal strength. Thus, this asymmetry may vary from equipment to equipment and from time to time (as atmospheric conditions change) in service.

Frequency shift channels are generally symmetrical in their response when the discriminator in the receiver is balanced. If the discriminator is biased to one side or the other the receiver output tends to favor the side to which it is biased.



FDH – High set fault detector (overcurrent)
FDL – Low set fault detector (overcurrent)
SQ. AMP – Squaring amplifier

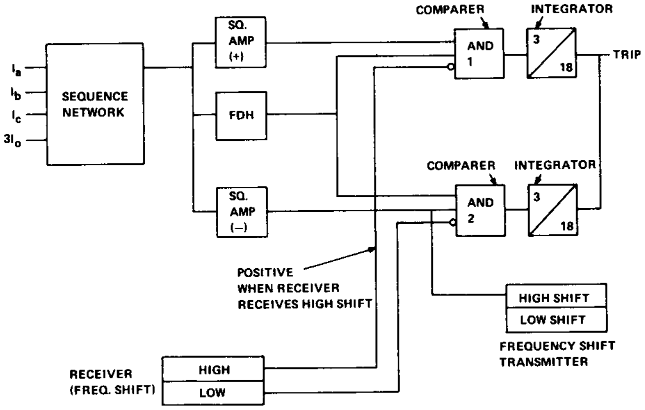
FDH provides continuous output when the sequence network output exceeds the pick-up setting.

FDL provides continuous output when the sequence network output exceeds the pick-up setting.

SQ. AMP (+), provides an output only during positive half cycle.

SQ. AMP (–), provides an output only during negative half cycle.

Figure 15. Dual Phase-Comparison Tripping Scheme



FDH – High Set fault detector (overcurrent)
SQ. AMP – Squaring Amplifier

FDH provides continuous output when the sequence network output exceeds the pick-up setting.

SQ. AMP (+) provides an output only during positive half cycle.

SQ. AMP (–) provides an output only during negative half cycle.

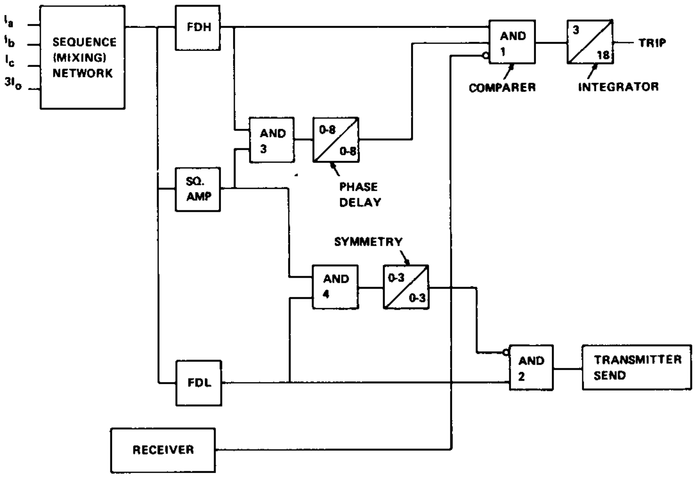


Figure 16. Dual Phase-Comparison Blocking Scheme

Figure 17. Single Phase-Comparison Blocking Scheme

Because of this, all phase comparison schemes that may operate with asymmetrical channels are equipped with a symmetry adjustment. Figure 17 illustrates the same scheme as that of Figure 4 except that it includes a symmetry adjustment and a phase delay adjustment feature. The phase delay adjustment will be discussed subsequently.

The symmetry adjustment (0-3/0-3) is in the keying circuit to the transmitter. It is set with either a time delay pickup or a time delay drop out depending on whether the receiver elongates or shortens the received signal. The time setting is made in the field after the transmitters, receivers, and coupling equipment have all been tuned and adjusted for proper sensitivity. The proper setting is obtained by keying the transmitter on and off by means of a symmetrical sinusoidal output from the mixing network. Then, while this is taking place, the time delay pickup or dropout of 0-3/0-3 is adjusted so that the remote receiver yields a symmetrical output.

The results of the symmetry adjustment are twofold. First, the remote receiver output is symmetrical, and second the keying signal may be phase shifted in the lagging direction from the actual squaring amplifier output. This latter result is not desirable, but fortunately it may be mitigated. It is obvious that if the keying signal is shifted in phase from the local squaring amplifier output, the remote received signal will be phase shifted from the current at the keying terminal. In addition to this there is the propagation delay in getting the communication signal from the transmitter to the remote receiver (1 millisecond per 186 miles) plus the delay in the receiver itself. All of these add to each other to produce a receiver output that may be significantly phase delayed from the current at the remote end of the line. This is undesirable because it introduces an error in the phase comparison. There is no way to eliminate this phase delay but there is a way to compensate for it. This compensation is accomplished by the phase delay timer (0-8/0-8) in the comparer input circuit.

PHASE DELAY ADJUSTMENT

The phase delay timer (0-8/0-8) is a timer that is set with a pickup and a dropout delay that are equal to each other so that it introduces a phase delay. Its output is the same shape as that of the squaring amplifier but delayed in time by the setting. This time delay setting is made in the field to be just equal to the sum of the three delays (symmetry adjustment, propagation, and receiver) discussed above. Thus, with this arrangement in the blocking scheme of Figure 17, an external fault would produce a receiver output exactly in phase and symmetrical with the output of the phase delay timer. This is necessary for proper blocking. For internal faults the output from the phase delay timer would be symmetrical with, but 180 degrees out of phase with the receiver output. This is necessary for tripping. It should be recognized that any errors in these adjustments can reduce the tripping margins for internal faults and/or reduce the blocking margins during external faults.

It is interesting to note that the setting of the phase delay timer is dependent on the channel operating time, and that the total tripping time of the scheme is affected by this timer setting. Thus, the tripping speed of the scheme is to that degree dependent on the channel operating time.

TRANSIENT BLOCKING

Transient blocking is a feature that is included in all phase comparison schemes. It adds to the security of the scheme during and immediately after the clearing of external faults. Figure 18 is a representation of Figure 17 except with the transient blocking logic added. This consists of AND6 and the 20-40/40 timer.

The basic logic of the transient blocking scheme is such that if a fault is detected, as indicated by the operation of FDH, but no trip takes place, as indicated by no output from the integrator (3/18) timer, AND/6 produces an output to the transient blocking timer (20–40/40). If this condition persists for a time that is long enough for the transient blocking timer to produce an output, tripping is blocked via the NOT input to AND5. This blocking of a trip output persists for 40 milliseconds after AND6 output disappears as a result of FDH resetting or 3/18 producing an output.

The pickup time delay setting of the transient blocking timer is somewhat longer than the expected time difference between FDH pickup and a 3/18 output during an internal fault. This insures no delay in tripping in the event of an internal fault, as well as prolonged blocking during the clearing of an external fault during which transient power reversals may tend to cause false tripping. Actually this transient blocking feature provides an *added* margin of security since the scheme is designed to be secure without this circuitry.

SUMMATION

It should be recognized that while the discussions in this section were strongly oriented toward a blocking scheme over an ON-OFF channel, the same or similar comments and circuits apply to all the other schemes. In some cases, for one reason or another, these functions may differ somewhat in arrangement from the logic illustrated in Figure 18. For example, it is obvious that the symmetry adjustment may be left out of the keying circuit if it is included in the output of the receiver, and in some applications this is done. In some cases of frequency-shift equipment, the symmetry adjustment is an integral part of the receiver, and so would not be shown on the logic diagram. In any case these functions are included in all schemes in one form or another.

MULTI-TERMINAL LINES

Up to this point these discussions have pertained principally to two-terminal lines. Phase comparison schemes are often applied to lines having more than two terminals and those applications differ somewhat depending on the channel equipment.

ON-OFF CHANNEL

The ON-OFF channel equipment is invariably used in blocking type carrier schemes similar to that of Figure 18. Since this type of scheme utilizes only one common frequency for all the transmitters and receivers, Figure 18 will apply to multi-terminal lines as well as two terminal lines. A blocking signal sent from any terminal will be received at all the other terminals to provide the necessary blocking via the single receiver at that terminal.

Since all the receivers and transmitters operate at the same frequency, each receiver will receive its own local transmitters as well as all the remote transmitters. It will be recalled that the symmetry adjustment in the keying circuit is based on the response of the *remote* receiver. Since the attenuation between a transmitter and its local receiver may be quite different from what it is between the same transmitters and a remote receiver, it is reasonable to expect that the output of a receiver responding to a local transmitter will not be symmetrical. Thus, during internal faults, even assuming that the currents at all the line terminals are exactly in phase, it is quite possible that the receivers will produce outputs somewhat longer than a half cycle. This is true for two-terminal lines as well as multi-terminal lines but it can be more exaggerated on multi-terminal lines because of the added transmitters and adjustments that may not be exactly correct.

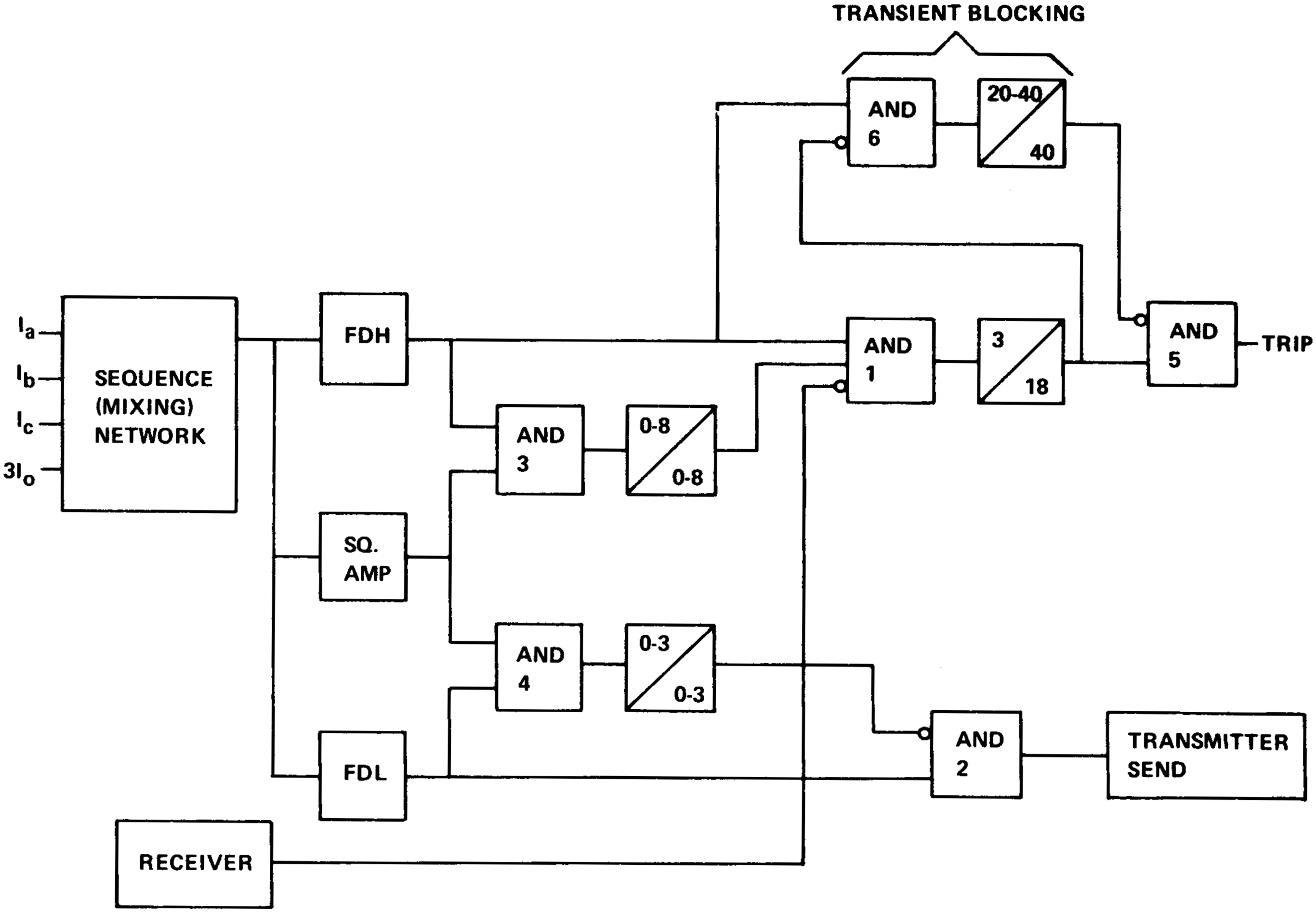


Figure 18. Single Phase-Comparison Blocking Scheme

While the situation described above will reduce the margin for tripping on internal faults, it is not generally a problem if proper sensitivity settings are made on the receivers, and careful and proper symmetry and phase delay adjustments are made on the relays as well. The use of hybrids to attenuate the strength of the transmitted signal as received by the local receiver can also be helpful. These are available on some of the newer carrier sets and they tend to make the received local transmitter signals appear weaker than the remote transmitter signals.

It is of interest to recall in passing that in mixed excitation (positive plus negative) schemes during internal faults, the mixing network output currents at all terminals are *not* exactly in phase with each other. This in itself cuts down the tripping margin, and any additional loss of margin from the items discussed above is that much more undesirable.

FREQUENCY-SHIFT CHANNEL

Frequency-shift channels are generally used in tripping type schemes. Figure 19 illustrates a three-terminal line tripping scheme using a frequency-shift channel. This arrangement requires two receivers at each terminal. One receiver is required for each remote transmitter because each transmitter is operated at a different frequency. In order to trip, a high-shift output is required from both receivers concurrently to AND2. A two-terminal line scheme would require only one receiver which would operate directly into AND1 without the need for AND2.

Frequency-shift channels are inherently symmetrical, and they do not receive their own locally-transmitted signals. Because of this, schemes using this type of channel are not generally troubled by the symmetry problems of the ON-OFF carrier channels.

STANDARD SCHEMES

In the foregoing discussions it was pointed out that phase comparison relaying can be accomplished in many different ways. These differences relate to such factors as:

1. The type of excitation that is used.

2. The type of transmitter-receiver that is used.

3. The type of channel link that is used.

4. The operating mode – blocking vs. tripping, single vs. dual, mho supervision vs. no mho supervision.

While all the different combinations were discussed and illustrated to some degree, not all of them are used in practice. For the most part there are some so-called standard schemes that are most popular because of a combination of such factors as overall performance, cost, and simplicity. It should also be recognized that the discussions and logic diagrams discussed were basic and generally rudimentary in order to present the fundamental concepts. Actually the various schemes often involve more detailed considerations and may appear somewhat different when their logic diagrams are compared to those discussed. However, the basic concepts are the same.

Table II presents a listing of typical schemes in use today. It will be noted that all the schemes listed in this table except the last two provide complete protection against single-phase-to-ground as well as multi-phase faults. The last scheme requires additional equipment for three-phase faults. The next to last scheme requires additional equipment for all multi-phase faults.

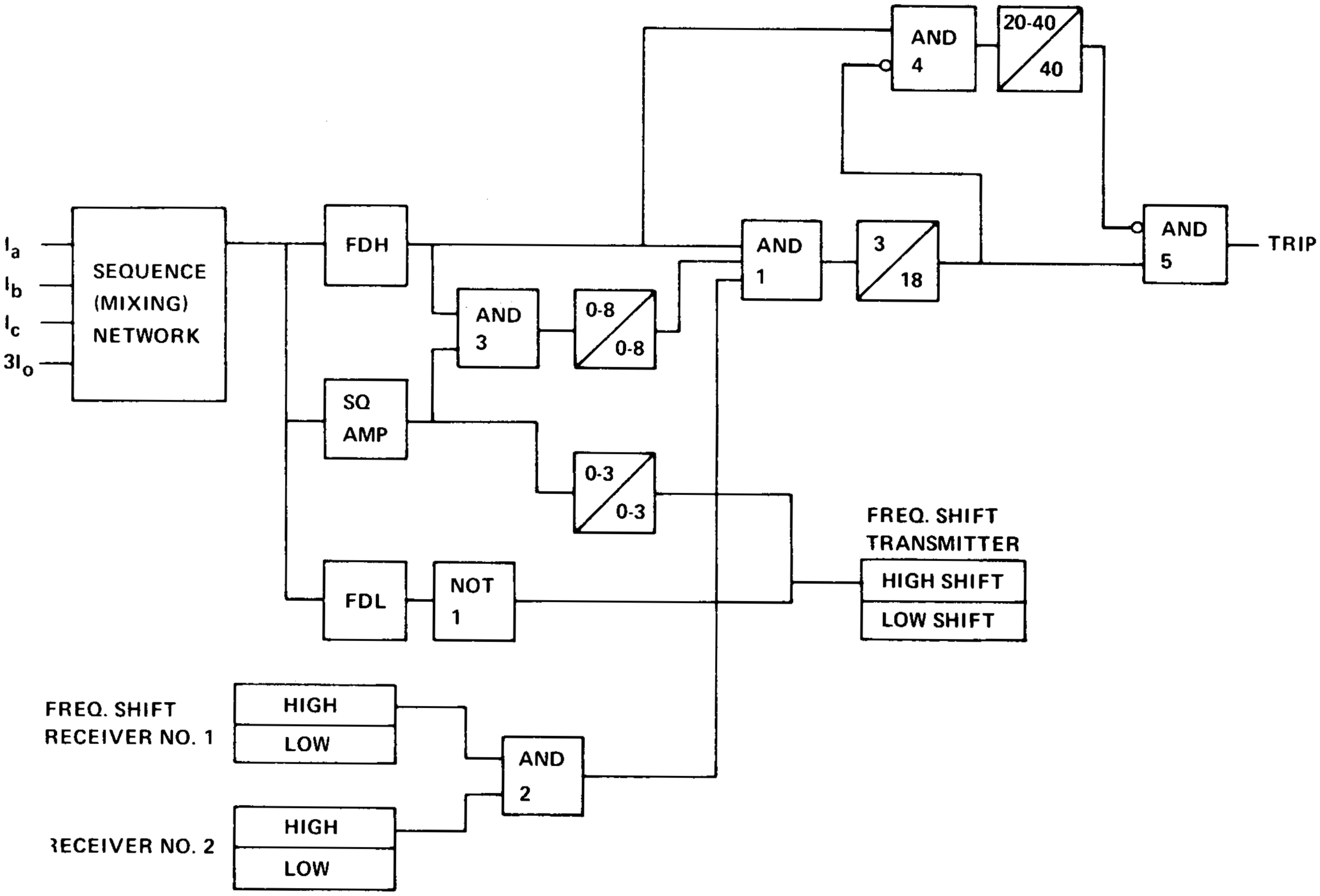


Figure 19. Single Phase-Comparison Tripping Scheme

TYPE OF SCHEME	EXCITATION	BLOCKING VS TRIPPING	CHANNEL	SINGLE VS DUAL
NETWORK UNBALANCING	I_2 SWITCHED TO I_1 DURING 3 PHASE FAULTS	BLOCKING TRIPPING	ON–OFF CARRIER (2) FREQ SHIFT MICROWAVE	SINGLE
COMBINED PHASE AND DIRECTIONAL COMPARISON	I_2	BLOCKING	ON–OFF CARRIER	SINGLE
COMBINED PHASE AND DIRECTIONAL COMPARISON	I_0	BLOCKING	ON–OFF CARRIER	SINGLE
PHASE COMPARISON	$I_2 - \frac{I_1}{K}$	BLOCKING TRIPPING	ON–OFF CARRIER (2) FREQ. SHIFT MICROWAVE	SINGLE
PHASE COMPARISON WITH DISTANCE RELAY SUPERVISION	$I_2 - \frac{I_1}{K}$	BLOCKING TRIPPING	ON–OFF CARRIER (2) FREQ. SHIFT MICROWAVE	SINGLE
PHASE COMPARISON	$I_2 - \frac{I_1}{K}$	TRIPPING	(3) FREQ. SHIFT MICROWAVE	DUAL
PHASE COMPARISON WITH DISTANCE RELAY SUPERVISION	$I_2 - \frac{I_1}{K}$	TRIPPING	(3) FREQ. SHIFT MICROWAVE	DUAL
PHASE COMPARISON	I_0*	TRIPPING	(3) FREQ. SHIFT SINGLE SIDE BAND	DUAL
PHASE COMPARISON	I_2∆	BLOCKING TRIPPING	ON–OFF CARRIER (2) FREQ. SHIFT MICROWAVE	SINGLE

* PROTECTS AGAINST GROUND FAULTS ONLY

∆ PROTECTS AGAINST ALL BUT THREE-PHASE FAULTS

Table II. Popular Phase Comparison Schemes