15 LINE PROTECTION WITH PILOT RELAYS

Pilot relaying is the best type for line protection. It is used whenever high-speed protection is required for all types of short circuits and for any fault location. For two-terminal lines, and for many multiterminal lines, all the terminal breakers are tripped practically simultaneously, thereby permitting high-speed automatic reclosing. The combination of high-speed tripping and high-speed reclosing permits the transmission system to be loaded more nearly to its stability limit, thereby providing the maximum return on the investment.

The continuing trend of increasing circuit-breaker-interrupting capabilities is increasing the allowable magnitude of short-circuit current. It is quite possible that damage rather than stability may dictate high-speed relaying in some cases.

Pilot relaying is used on some multiterminal lines where high-speed tripping and reclosing are not essential, but where the configuration of the circuit makes it impossible for distance relaying to provide even the moderate speed that may be required.

Some lines are too short for any type of distance relay. For such lines, it is not merely a matter of getting a distance relay with a lower minimum ohmic adjustment; the ohmic errors would be so high as compared with the ohms being measured that such relaying would be impractical.

Critical loads may require high-speed tripping beyond the capabilities of distance relays.[11]

For these reasons, it is the practice to use pilot relaying for most high-voltage transmission lines and for many subtransmission and distribution circuits. Therefore, it becomes necessary to choose between wire pilot, carrier-current pilot, and microwave pilot.[2] If either of the last two is indicated, one has to choose further between phase comparison and directional comparison, or a combination of the two. In addition to any of these, some form of remote tripping may be required. The application considerations of these various equipments will now be discussed.

WIRE-PILOT RELAYING

Chapter 5 tells why d-c wire-pilot relaying has largely given way to a-c types. In this chapter, we shall consider the application of only the a-c types.

Wire-pilot relaying is used on low-voltage circuits, and on high-voltage transmission lines when a carrier-current pilot is not economically justifiable. For the protection of certain power-cable circuits, wire pilot may be used because the cable-circuit attenuation is too high for carrier current. For short lines, a-c wire-pilot relaying is the most economical form of high-speed relaying.

Generally, wire pilots no longer than about 5 to 10 miles are used, but there are a few in service as long as about 27 miles.[3] As mentioned in Chapter 5, the technical limitations on the length of a pilot circuit are its resistance and shunt capacitance. Compensating reactors are sometimes used when the shunt capacitance is too high. A pilot circuit that is rented from the telephone company may be much longer than the transmission line for whose protection it is to be used, because such telephone circuits seldom run directly between the line terminals. Therefore, in borderline cases, one should find out the actual resistance and capacitance before deciding to use wire pilot. Other requirements imposed on the wire-pilot circuit are described in Chapter 5.

In general, wire-pilot relaying is not considered as reliable as carrier-current-pilot relaying, mostly because many of the wire-pilot circuits that are used are not very reliable. The pilot circuit represents so much exposure to the possibility of trouble that great care should be taken in its choice and protection.

OBTAINING ADEQUATE SENSITIVITY

Apart from making sure that associated equipment is suitable for the application, the principal step in the application procedure is to determine if the available adjustments of the relaying equipment are such that the necessary sensitivity and speed are assured. Manufacturers' bulletins describe how to do this when one knows the maximum and minimum fault-current magnitudes for phase and ground faults at either end of the line.

It is advisable not to adjust the equipment to have much greater sensitivity than is required or else, in so doing, the CT's may be burdened excessively. With excessive burden, the overall sensitivity may be poorer, as illustrated by Problem 2 of Chapter 7.

If the phase-fault currents are high enough to permit it, it is advisable to adjust the phase-fault pickup to be at least 25% higher than maximum load current. Then, the equipment will not trip its breakers undesirably on load current should the pilot wires become open-circuited or short-circuited. Undesirable tripping could still occur for an external fault, unless supervising equipment is used to forestall such tripping.

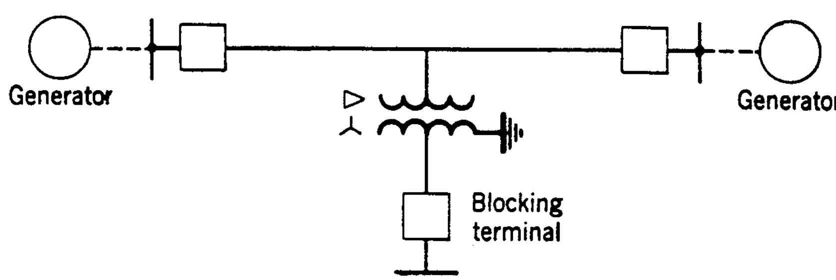


Fig. 1. Illustrating a blocking-terminal application.

When there are sources of generation back of more than two terminals, or if there are grounded-neutral wye-delta power-transformer banks at more than two terminals, the application requires a careful study of the available short-circuit currents under various generating conditions to determine if the necessary sensitivity can be assured. The more source terminals there are, the less sensitive will the protection be.[4]

When there are sources of generation back of only two terminals as in Fig. 1, the problem is much simplified. A terminal that has no source of generation is treated as a so-called "blocking" terminal. Instantaneous overcurrent relays energized from CT's on the high-

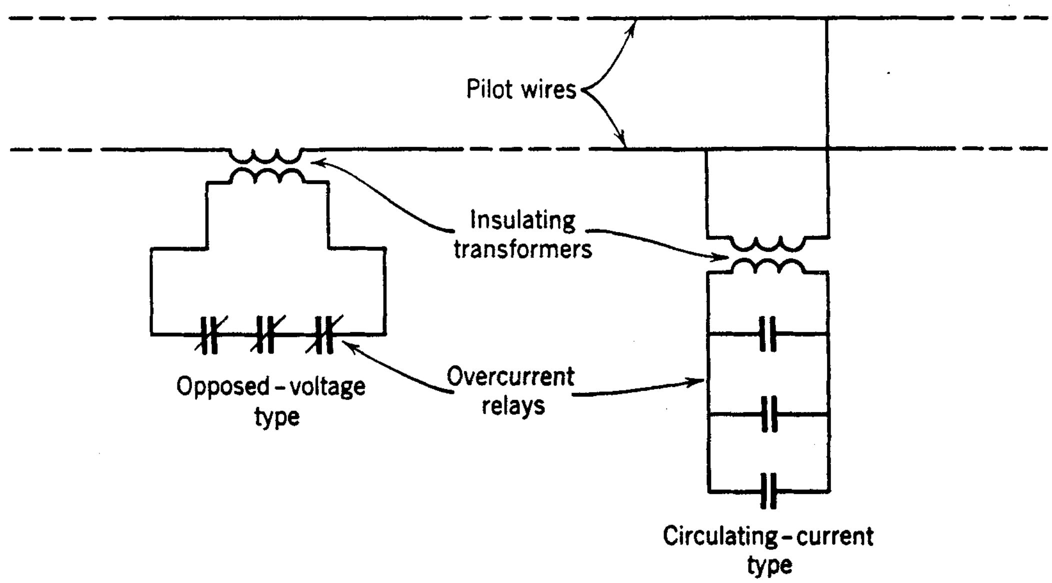


Fig. 2. Blocking-terminal technique.

voltage side of each blocking terminal are connected either to open-circuit or to short-circuit the pilot wires, depending on the type of wire-pilot relaying used, to block tripping at the main terminals for a low-voltage fault at the blocking terminal. The operating time of the tripping relays at the main terminals must be coordinated with that of the blocking-terminal relays. The overcurrent-relay contacts operate in the secondary of an insulating transformer, as in Fig. 2. It is necessary to energize the blocking relays from high-voltage CT's so that tripping at the source terminals will also be blocked for magnetizing-current inrush. The blocking relays should not be sensitive enough to operate on the current fed back to high-voltage faults by motors on the low-voltage side of the blocking terminal, or else tripping at the main terminals will be delayed.

Blocking-terminal equipment will not trip the local breaker for high-voltage line faults; such tripping may be necessary if automatic reclosing is used at the source terminals of the line and if there are motors at the blocking terminal that might be damaged by such reclosing. If high-speed reclosing is used at the source terminals, the breaker at the blocking terminal must be tripped, when necessary, by remote tripping from both source terminals. If the automatic reclosing is slow enough, the breaker could be tripped by local undervoltage or underfrequency relays.

If a blocking-terminal power-transformer bank is large enough to justify differential relaying, remote tripping of the source terminals for transformer faults would be used if there were no high-voltage breakers at the blocking terminal, as is usually true.[5] Otherwise, the bank would be protected only by fuses on the high-voltage side.

For the blocking-terminal technique to be permissible, the total load current of all blocking terminals on the line must be less than the current required to operate the wire-pilot relays at one source terminal of the line with the breaker at the other source terminal open.

If the power-transformer banks are small enough at the load terminals behind which there is no generation, the wire-pilot relays at the source terminals could be adjusted not to operate for low-voltage faults at the load terminals. This would also probably prevent operation on magnetizing-current inrush, particularly if the ground-fault pickup could be made high enough.[6] This would eliminate the need for any blocking-terminal equipment.

A multiterminal line can sometimes be well protected against ground faults with wire-pilot relaying, even though adequate phase-fault protection is impossible. This is because line taps are usually made through delta-wye power-transformer banks, and they are open circuits so far as zero-phase-sequence currents on the high-voltage side are concerned. Therefore, if the wire-pilot relays are arranged to receive only the CT neutral current, such a multiterminal line may be treated as a two-terminal line. Good protection against phase faults on such a line can often be provided by distance relays because the impedance of the transformer at each tap is so high that the distance relays can usually be adjusted to protect 80% to 90% of the line without reaching through any of the transformers.

CURRENT-TRANSFORMER REQUIREMENTS

Conventional a-c wire-pilot relays have variable percentage-differential characteristics that permit large CT ratio errors at high magnitudes of external-fault currents. Usually, it is only necessary to be sure that the CT's are able to supply the required current to operate the relays at high speed when internal faults occur. This is a matter involving the relay burdens for the sensitivity taps used, the pilot-wire resistance, and the characteristics of the CT's.

The equipment may also contain adjustment to compensate for the nominal CT ratio at one terminal differing from that at another terminal. In borderline cases, this adjustment might increase a tendency to operate undesirably for external faults because of transient differences between CT errors; therefore, in general, the same nominal CT ratios at all terminals are preferred.

If a line terminates in a power-transformer bank with no high-voltage breaker, the relaying equipment should be energized from high-voltage CT's–generally bushing CT's in the transformer bank. If low-voltage CT's were used, they would have to be connected so as to compensate for the phase shift caused by the power transformer and, possibly, to remove zero-phase-sequence components. The objection to low-voltage CT's is that the relaying equipment will operate to trip undesirably on magnetizing-current inrush either when the transformer bank is energized or when system disturbances occur. To avoid such objectionable operation would require additional relaying equipment. Also, some types of a-c wire-pilot relays would not respond to faults between a particular pair of phases.

BACK-UP PROTECTION

Wire-pilot relaying does not provide back-up protection. Separate overcurrent or distance relays are used for this purpose. When wire-pilot relaying is applied to an existing line, it is often the practice to use the existing relaying equipment for back-up protection.

Distance relays may be used for back-up protection even though the line is too short to use distance relays for primary protection. In such a case, the high-speed zone would be made inoperative.

When directional-overcurrent relays are used for back-up protection, the requirements on the voltage source are the least severe, and uncompensated low-tension voltage can be used. It will be noted that the conventional type of a-c wire-pilot-relaying equipment does not use any a-c voltage.

CARRIER-CURRENT-PILOT RELAYING

Carrier-current-pilot relaying is the best and most commonly used kind of relaying for high-voltage lines. A report[7] showed that this kind of relaying is in service on lines whose voltage is as low as 33 kv. It is applicable in some form to any aerial line. Carrier-current-pilot relaying is preferred to wire-pilot relaying because it is somewhat more reliable and is more widely applicable. Consisting entirely of terminal equipment, it is completely under the control of the user, as contrasted with rented wire pilot. Also, the carrier-current pilot lends itself more conveniently to joint usage by other services such as emergency telephony and remote trip.

AUTOMATIC SUPERVISION OF THE CARRIER-CURRENT CHANNEL

When carrier-current-pilot relaying was first introduced, the reliability of vacuum tubes was not as good as it is now, and some users felt the need for automatic equipment to supervise the pilot channel. Today, users are content to rely on the manual tests that are made daily at various regular intervals because the carrier-current channel has proved to be a very reliable element of the protective equipment.[7]

CARRIER-CURRENT ATTENUATION .

Every proposed application should be studied to be sure that the losses, or attenuation, in the carrier-current channel will be within the allowable limits of the equipment.[8] Manufacturers' publications specify these limits and describe how to calculate the attenuation in each element of the channel.[9]

The protection of multiterminal lines requires very careful scrutiny of the attenuation. Depending on the length of line tapped from the main line, "reflections" from a tap may cause excessive attenuation unless the carrier-current frequency is very carefully chosen. If this length is $1/4$, $3/4$, $5/4$, $7/4$, $9/4$, etc., wavelengths, excessive attenuation may be expected. Sometimes, only a test with carrier current of different frequencies will supply the required information.[10] In extreme cases, it is necessary to install line traps in the taps to eliminate reflections.

Power cable causes very high carrier-current attenuation, particularly where sheath-bonding transformers are used. Also, the so-called "mismatch," or discontinuity in the impedance characteristic of the channel where power cable connects to overhead line, causes high loss.[11] It is usually possible to use carrier current only on short lengths of cable, and then only with frequencies near the low end of the range. Because of the foregoing, wire pilot, or even microwave pilot, is sometimes used where carrier current might otherwise be preferred.

USE OF CARRIER CURRENT TO DETECT SLEET ACCUMULATION

The carrier-current channel provides a method for determining when sleet accumulation requires sleet melting to be started. This method has had varied reception among electric utilities.[12] It is generally agreed that the method indicates sleet accumulation, but it will also occasionally give false indication during fog, mist, or rain. Those who use this method of sleet detection feel that the extra cost incurred as a result of going through the sleet-melting process unnecessarily because of such false indications is small and is justified on a "fail-safe" basis.

The method of detecting sleet accumulation is based on the fact that the attenuation of a transmission line increases as sleet accumulates on the line. Figure 3 shows the effect of attenuation on the magnitude of the output from the carrier-current receiver. Normal operation is represented by the point *A*. The safety factor in the equipment, when it is properly applied, is sufficient so that under the most adverse atmospheric conditions, including sleet, the attenuation would not greatly exceed that represented by the point *B*.

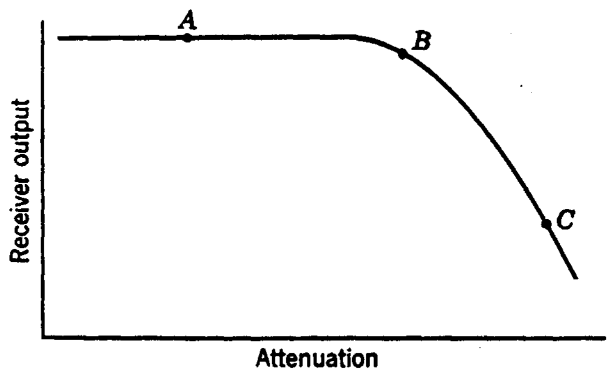


Fig. 3. Effect of attenuation on the strength of the receiver-output signal.

Therefore, the reliability of the equipment is assured under all conditions. Now, when it is desired to detect sleet accumulation, the operator at one end of the line causes carrier current to be transmitted, and the operator at one end or the other presses a button to introduce attenuation into the transmitter or receiver circuit so as to advance the normal operating position from *A* to *B*. Then, the receiver output decreases rapidly for any additional attenuation due to sleet. When conditions appear to be favorable for sleet, such a test at frequent intervals will detect increases in sleet accumulation. Such information must be coordinated with visual observation and experience before the receiver-output readings have any useful meaning.

This sleet-detection feature also detects accumulation of dirt or salt on the line insulators, and deterioration of vacuum tubes. It is used for this purpose by many companies that do not use it for sleet detection.

TYPES OF RELAYING EQUIPMENT

The three types of carrier-current-pilot-relaying equipment in regular use are phase comparison, directional comparison, and combined phase and directional comparison. Each of them will be treated in the following material.

PHASE COMPARISON

Phase-comparison relaying is much like a-c wire-pilot relaying. It is the simplest conventional type of carrier-current-pilot-relaying equipment. However, its best application is to two-terminal lines; multiterminal-line applications require very careful examination, and the sensitivity of the protection is quite inferior to that for two-terminal lines. Even for two-terminaI lines, the phase-fault sensitivity of phase comparison is not as good as that of directional comparison.

The ideal application of phase comparison is to a two-terminal line that one is sure will not be tapped later, and where the fault-current magnitudes are high enough to assure high-speed tripping under all likely conditions of system operation.

The fact that phase-comparison relaying does not use a-c voltage (except for testing) may or may not be an advantage, depending on the type of back-up relaying that is used. If distance relays are used for back-up, the same quality of voltage source is required as for directional-comparison relaying. It is only when overcurrent relaying (possibly directional) is used for back-up protection that phase-comparison relaying enjoys any advantage from not using a-c voltages.

Phase-comparison relaying is unaffected by mutual induction from neighboring power circuits. This is an advantage over directional comparison. This subject is treated in more detail later under the heading "Combined Phase and Directional Comparison."

The fact that any back-up-relaying equipment that may be used is entirely separate from the phase-comparison equipment is an advantage of phase comparison. One equipment may be taken out of service for maintenance without disturbing the other in any way.

An excellent comparison of phase and directional-comparison relaying is given in Reference 13.

OBTAINING ADEQUATE SENSITIVITY

Apart from making sure that the carrier-current attenuation is not too high, and that associated equipment is suitable for the application, the principal step in the application procedure is to determine if the available adjustments of the relaying equipment are such that the necessary sensitivity and speed are assured. Manufacturers' bulletins describe how to do this when one knows the maximum and minimum fault-current magnitudes for phase and ground faults at either end of the line..

It is advisable not to adjust the equipment to have much greater sensitivity than is required or else, in so doing, the CT's may be burdened excessively. With excessive burden, the overall sensitivity might be poorer, as illustrated by Problem 2 of Chapter 7. Or, if the ground-fault sensitivity is too high, the equipment might misoperate on "false residual currents"[6] caused by CT errors because of external-fault current having a large d-c offset, or because of differences in residual flux.

In practice the equipment is usually adjusted so that carrier current is not generated unless the phase-fault current exceeds the maximum load current. The purpose of this is to prolong the life of the vacuum tubes and to make the carrier-current channel available for other services when it is not required for relaying. Because the pickup of the tripping fault detectors must be higher than the pickup of the blocking fault detectors, the tripping pickup will be still higher above maximum load; in fact, the *reset* value of the tripping fault detectors must be a safe margin above the pickup of the blocking fault detectors. With such adjustment, failure of the carrier-current channel will not cause undesired tripping under load; however, undesired tripping could occur for an external fault if the channel failed.

THE PROTECTION OF MULTITERMINAL LINES

The more terminals there are with sources of generation back of them, the less sensitive will the protection be. This is illustrated with the help of Fig 4 for a three-terminal line. Should equal magnitudes of fault current be fed into terminals *A* and *B* for an external fault beyond *C*, the pickup of the tripping fault detectors at *C* would have to be more than

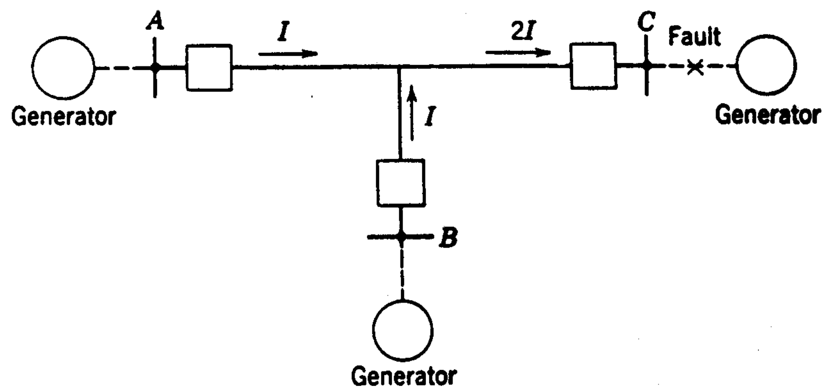


Fig. 4. Illustrating the reduction of sensitivity of phase-comparison relaying on multiterminal lines.

twice as high as the carrier-current-starting, or blocking, fault detectors at *A* and *B*. And, if the blocking fault detectors are adjusted to reset at more than the maximum full-load current, the tripping fault detectors at *C* will have to be adjusted to pick up at about 3 times maximum load.[14] Remember that phase-comparison relaying is not directional and that one terminal will operate to trip whenever its current is high enough unless it receives a blocking carrier-current signal from another terminal. The worst case is with equal currents entering at *A* and *B*. If one can be sure that these currents will not be equal, the tripping-fault-detector pickup at *C* can be lowered.

In general, the pickup adjustments of the fault detectors do not have to be the same at all terminals, but the pickup of the blocking fault detector having the highest pickup must be lower than the reset of the tripping fault detector having the lowest pickup.

Occasionally, in order to get the required tripping sensitivity, it may be considered justifiable to increase the blocking sensitivity to the point at which carrier current is transmitted continually when full-load current is flowing. In that event, vacuum-tube life will be shortened and the carrier-current channel cannot be used for any other services.

Another way of avoiding high pickup of the tripping fault detectors for situations like Fig. 4 is to use directional relays to control tripping at places like terminal *C*. However, this kind of solution will not work for the situation illustrated by Fig. 5 where the same problem exists, but at a terminal where the large current is flowing in the tripping direction.

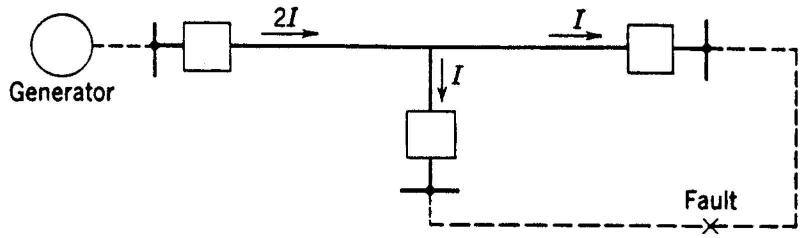


Fig. 5. A situation in which directional relaying will not prevent reduced sensitivity.

At a load terminal, back of which there is no source of generation, and where there is no power-transformer neutral grounding on the high-voltage side, blocking-terminal equipment consisting of instantaneous overcurrent relays and a carrier-current transmitter can be used to block tripping at the main terminals for faults in the load circuits. Of course, this is necessary only if the main-terminal equipment is sensitive enough to operate for low-voltage faults at a load terminal. The phase-sequence network, comparer, etc., that are used in the equipment at the main terminals are not necessary, since no tripping function is provided at the blocking terminal. To block tripping at the main terminals, the overcurrent relays simply turn on carrier that is transmitted continuously and not every other half cycle. The blocking relays should be energized from CT's on the high-voltage side of the load-terminal power-transformer bank so that tripping will be blocked on magnetizing-current inrush. If the power transformer is wye-delta and grounded on the wye side, a ground overcurrent relay would be required to shut off carrier for ground faults on the high-voltage side.

If tripping at a blocking terminal is required to avoid damage to large motors when automatic reclosing is used at the main terminals, such tripping will probably have to be provided by local underfrequency relays. Remote tripping by carrier current over the protected line from the main terminals to such a load terminal could not be assured unless the tripping of the main terminals will extinguish an arcing phase-to-ground fault that might be on the phase to which the carrier-current equipment is coupled. Synchronous

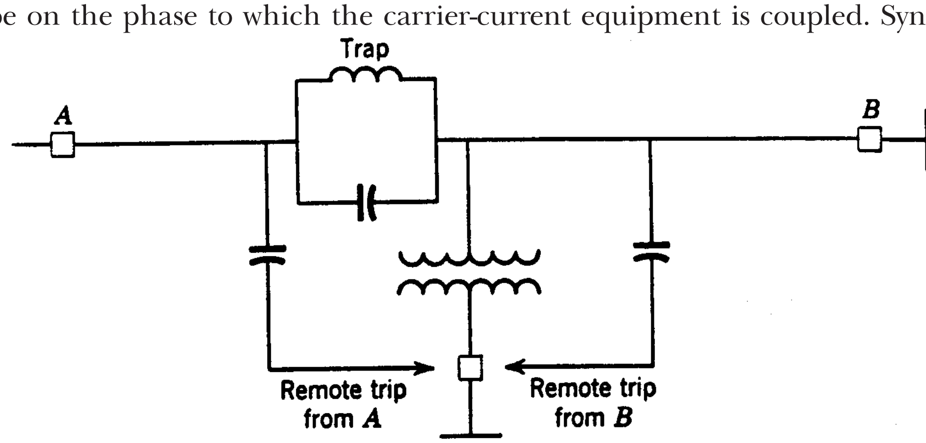


Fig. 6.. Method of avoiding interference by a fault with remote tripping.

motors, acting as generators, might be able to generate sufficient voltage to maintain an arc through the capacitance to ground of the unfaulted conductors. Some users have installed equipment that relies on transmitting sufficient carrier current for remote tripping past an arcing ground fault on the coupling phase, but such operation cannot be assured in general. One solution is to use phase-to-phase coupling for the remote-trip signal, or to transmit this signal over another line section if the lines are parallel. Another solution that has been used is shown in Fig. 6; no matter where the fault is, one main terminal or the other can cause remote tripping.

Remote tripping from power-transformer differential relays at a load terminal to the breakers at the main terminals can be done over the carrier-current channel.[5] Whenever remote tripping for transformer faults is undertaken, a line trap should be inserted in the coupling phase between the coupling capacitor and the power transformer, so that power-transformer faults to ground on the coupling phase cannot short-circuit the carrier-current-transmitter output.

A multiterminal line can sometimes be well protected against ground faults even though adequate phase-fault protection is impossible. This is because line taps are usually made through delta-wye power-transformer banks, which are open circuits so far as zero-phase-sequence currents on the high-voltage side are concerned. Therefore, if only ground relaying equipment is used and arranged to receive only the CT neutral current, such a multi terminal line may be treated as a two-terminal line.

BACK-UP PROTECTION

Phase-comparison relaying does not provide back-up protection. This should be provided by phase distance relays and either overcurrent or distance ground relays. When phase-comparison relaying is applied to an existing line, it is often the practice to use the existing relaying equipment for back-up protection.

Conventional back-up relaying will be inadequate when intermediate current sources supply so much current to a fault that the fault is put beyond the reach of the back-up relays. Such a problem and its solution are described in Chapter 14 under the heading "The Effect of Intermediate Current Sources on Distance-Relay Operation." In such a situation it will be at the discretion of the user whether, in addition to the special back-up equipment, conventional back-up equipment is also applied to provide primary relaying while the phase-comparison equipment is being maintained or repaired.

DIRECTIONAL COMPARISON

Directional-comparison relaying is the most widely applicable type, and therefore it lends itself best to standardization programs. The only circumstance in which directional comparison is not applicable is when there is sufficient mutual induction with another line and when directional ground relays are used instead of ground distance relays; this is treated at greater length later under "Combined Phase and Directional Comparison."

In general, apart from considerations of carrier-current attenuation, the application of directional-comparison relaying is largely a matter of applying phase distance and directional-ground or ground distance relays. This is because, as mentioned in Chapter 6, conventional equipment uses certain units in common for carrier-current-pilot primary relaying and for back-up relaying. In fact, if a line is now protected by phase distance relays and ground overcurrent or distance relays, one may merely need to add some supplementary relays plus the carrier-current equipment to apply directional-comparison carrier-current-pilot relaying; the supplementary relays and carrier-current equipment provide the blocking function while the existing relays provide the tripping function. Of course, completely separate relaying could be used, but it would be more expensive.

RELATION BETWEEN SENSITIVITIES OF TRIPPING AND BLOCKING UNITS FOR TWO-TERMINAL LINES

The principal application procedure is to be sure that the correct relations are obtained between the operating ranges of the blocking and tripping units. This is seldom a problem for a two-terminal line. Figure 7 shows the relative operating ranges of the blocking and tripping units at both ends of a two-terminal line for, say, phase faults. The significant observation is that, for external faults beyond either end of the line, the blocking units must reach out farther than the tripping units to be certain that, if there is any tendency to trip, it will surely be blocked. The tripping range for phase faults will be the operating range of the second- or third-zone distance-relay units, depending on the type of equipment.

The only time there is any problem adjusting the blocking units is when their range has to be so great that they might operate on load current, or that having operated for a fault they might not reset on load current. In such situations, it becomes necessary to use additional units called "blinders." These units are angle-impedance distance-relay units, one of which would be used with each blocking relay. The contacts of the two relays of each group would

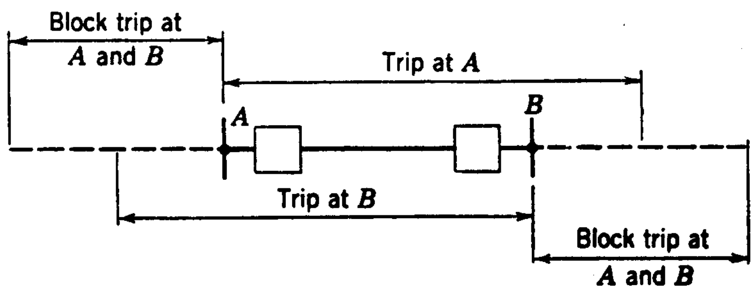


Fig. 7. Relative operating ranges of directional-comparison blocking and tripping units.

be connected in parallel so that both would have to open to start carrier. Figure 8 shows the operating characteristics of both relays and the point representing the load condition that makes blinders necessary. The resulting blocking region is shown cross-hatched. Blinders with impedance-type distance relays are shown because this type of relay is the most likely to require blinders for this purpose.

Incidentally, such blinders have been used also to prevent *tripping* on load current where distance relays have been applied to unusually long lines.

When low-tension voltage is used, transformer-drop compensation is not so necessary as when distance relays are used alone. The only time that transformer-drop compensation would be beneficial would be when the carrier-current equipment is out of service and complete reliance for protection is being placed on the distance relays. Such circumstances occupy so little of the total time that the additional complications of transformer-drop compensation are not justified.

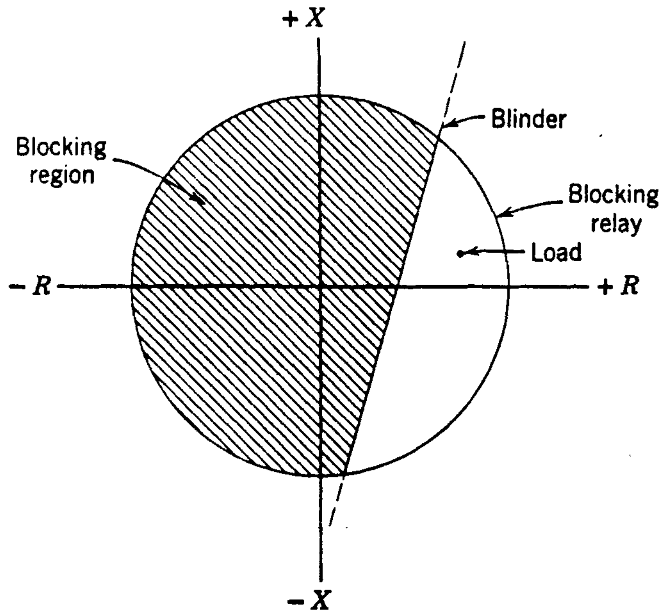


Fig. 8. A blinder to prevent blocking on load current.

The problem of obtaining the correct relations between the tripping and blocking units for multiterminal-line applications, along with other related problems, is treated next.

THE PROTECTION OF MULTITERMINAL LINES

Directional-comparison relaying is applicable to any multiterminal line. However, under some circumstances proper operation will not be obtained without a very careful choice of the type of equipment and of the blocking- and tripping-relay adjustments.[4,15] And sometimes simultaneous high-speed tripping at all terminals will not be obtained. Therefore, one should be familiar with these circumstances so as to be able to avoid them, if possible, in the early stages of system planning. These circumstances will now be described.

Current Flow Out of One Terminal for an Internal Fault. In Fig. 9, directional-comparison relaying cannot trip for an internal fault if the current flowing out of the line at *A* is higher than the blocking-relay pickup there. This situation may exist for phase faults or ground faults or both. If it is not permissible to raise the blocking relay pickup so as to avoid this situation, tripping must wait until the back-up relays at *B* trip their breaker, after which high-speed tripping can occur at the other two terminals.. For phase faults, the distance relays at *B* will operate at high speed, and sequential high-speed tripping of all other terminals can follow if there is enough fault current, and if other features of the equipment do not introduce time delay. For ground faults, the tripping of breaker *B* will be delayed slightly unless ground distance or instantaneous overcurrent ground relays are used.

Remote tripping from breaker B to the other terminals by means of carrier current over the protected line is not a reliable way to avoid sequential tripping, unless this type of difficulty occurs only for faults not involving ground. Or, if it occurs only for ground faults, phase-to-phase coupling could be used. Although some users are relying on getting sufficient remote-tripping signal past a phase-to-ground fault on the coupling phase, satisfactory results cannot be assured in general. Occasionally, another line section can be used for carrying the remote-tripping signal. Obviously, remote tripping would be practical if microwave were used instead of carrier current.

Insufficient Current for Tripping. Apart from there being too small a source of short-circuit current back of a terminal, other circumstances can make the current so low—or the apparent impedance to the fault so high—as to prevent or at least to delay tripping.

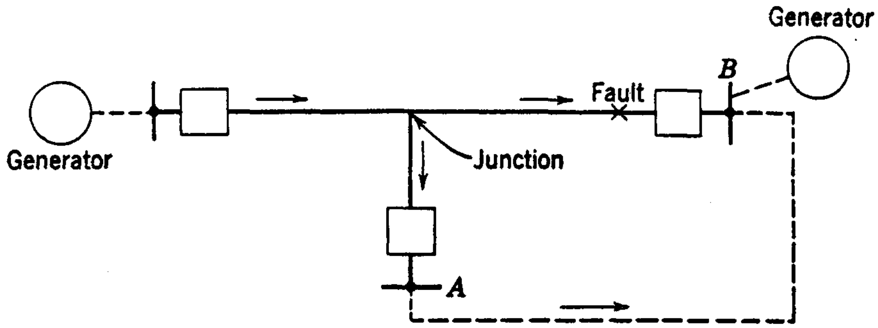


Fig. 9. Situation in which directional comparison blocks tripping for an internal fault.

For the circumstance of Fig. 9, if the fault is closer to the junction, the current at A will be: (1) in the blocking direction but too low to operate a blocking relay, (2) zero, or (3) in the tripping direction but too low to operate a tripping relay. For any of these, tripping at the other terminals would not be blocked, but tripping at *A* would have to wait until the breakers at *B* had tripped, assuming that there would then be a redistribution of enough fault current at A to cause tripping there.

Another circumstance in which the fault current may be too low is shown in Fig. 10. Here, the intermediate current, or "mutual impedance effect," as it is sometimes called, may prevent tripping at both *B* and *C*. Furthermore, the tripping of the breakers at *A* may not relieve the inability to trip at breakers *B* and *C*, so that even sequential tripping may not be possible.

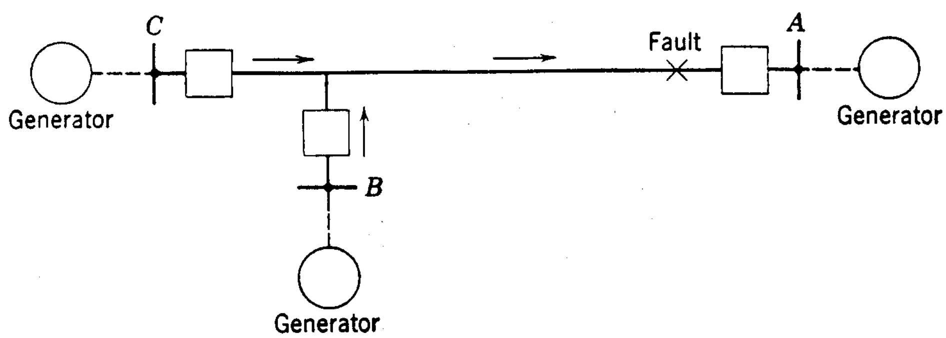


Fig. 10. Insufficient current for tripping.

As stated before, remote tripping is not a complete solution to the problem. Instantaneous undervoltage carrier-starting or tripping relays are a solution if their adjustments can be coordinated with those of the other relays.[2]

Shortcomings of Non-Directional Blocking Relays. Some directional-comparison equipments use non-directional overcurrent or impedance relays to start carrier. Occasionally, such equipments block tripping for an internal fault because the current or apparent impedance falls between the pickup of the blocking and tripping relays at the *same* terminal. Basically, the pickup adjustment of the blocking relays at a given terminal has to coordinate with the pickup adjustments of tripping relays at the other terminals. However, when non-directional blocking relays are used, coordination must also be obtained between the pickup adjustments of blocking and tripping relays at the *same* terminal. Such a circumstance can exist when there is insufficient current or too high an apparent impedance to cause tripping at a given terminal until after another terminal has tripped, as in one of the preceding cases. However, if a blocking relay at the given terminal should operate, it would block tripping at the other terminals; this situation would persist until a back-up relay operated to cause tripping at another terminal that would permit the given tripping relay to operate. The best solution to this problem is directional blocking relays.

Miscellaneous Problems of Coordinating Blocking and Tripping Sensitivities. It is necessary that the coordination between blocking and tripping sensitivities be carefully analyzed not only for multiterminal operation but also when a line is operated with one or more terminals open. Owing to elimination of intermediate current sources, such operation may increase the reach of the tripping relays at one terminal; one must be sure that these relays do not outreach the blocking relays at another terminal.

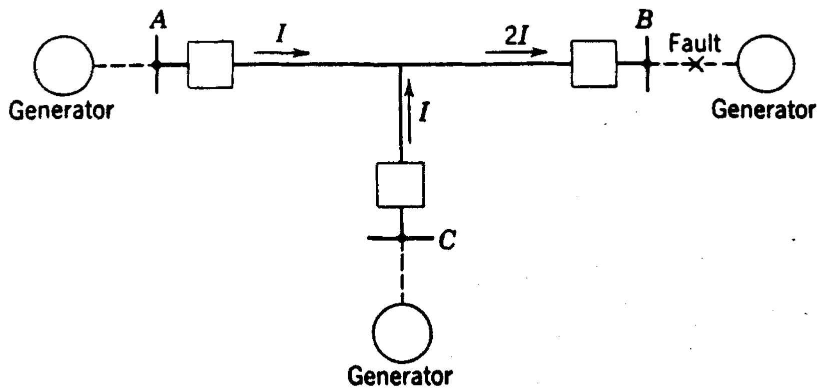


Fig. 11. Directional-comparison blocking relays get twice as much current as tripping relays.

Figures 11 and 12 show two extreme operating conditions for a three-terminal line, so far as the relative blocking and tripping sensitivities are concerned. For Fig. 11, the blocking relays at terminal *B* get twice as much current as the tripping relays at *A* or *C*; for Fig 12, the blocking relays at *B* and *C* get only half as much current as the tripping relays at *A*. Even greater extremes could exist for a line with more than three terminals.

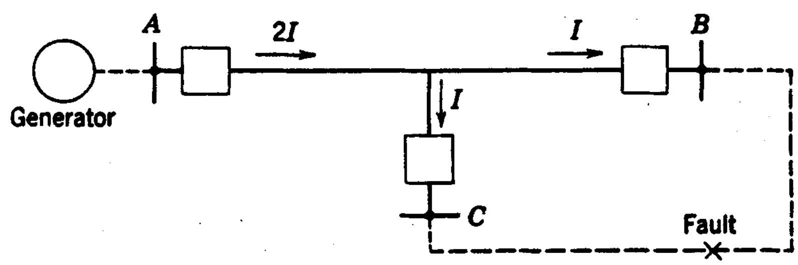


Fig. 12. Directional-comparison tripping relays get twice as much current as blocking relays.

Need for a Blinder on the Loss-of-Synchronism Blocking Relay. If the phase tripping relays at terminal *A* of Fig. 13 cannot operate to trip until after terminal *B* has tripped for the fault location *P*, a supplementary angle-impedance relay should be used to provide a "blinder" for the loss-of-synchronism blocking relay. The need for this blinder is shown in Fig. 14. The point P_1 represents the way the fault first appears to the tripping and blocking relays at *A*, and the point P_2 represents the appearance of the fault after *B* has tripped.

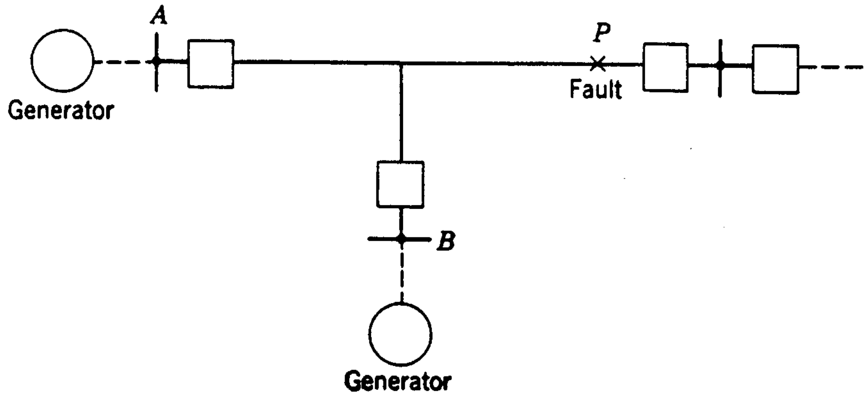


Fig. 13. Situation in which the loss-of-synchronism blocking relay will block tripping for an internal fault.

It will be noted that this sequence will establish local blocking at *A* by the loss-of-synchronism relay, and, consequently, that tripping there can only occur in third-zone time.

Figure 14 shows how the blinder characteristic modifies the operating characteristic of the blocking relay so that when the fault first occurs it will not fulfill the requirement for the second step in the sequence of operations necessary to set up loss-of-synchronism blocking. The effective blocking area is shown cross-hatched.

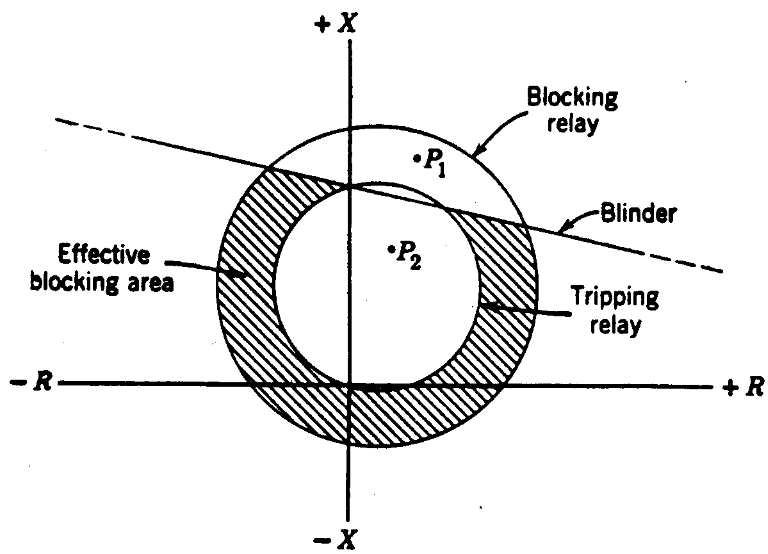


Fig. 14. R-X diagram of the conditions of Fig. 13.

Blocking-Terminal Equipment at Load Terminals. At terminals behind which there is no source of generation, only blocking equipment may be required. Such equipment is required if the high-speed relays at any of the main terminals are sensitive enough to operate for a low-voltage fault at such a load terminal. The blocking-terminal equipment consists of instantaneous overcurrent relays, energized from CT's on the high-voltage side of the power-transformer bank, and carrier-current transmitting and receiving equipment. The overcurrent relays start the transmission of carrier current to block tripping at the main terminals for low-voltage faults at the load terminal or for magnetizing-current inrush to the load-terminal power-transformer bank.

As described for phase-comparison relaying, remote tripping from a blocking-terminal power-transformer differential relay to the breakers at the main terminals can be accomplished over the carrier-current channel.[5]

EFFECT OF TRANSIENTS

Directional-comparison relaying using high-speed ground relays energized from zero-phase-sequence quantities is exposed to more possibilities of misoperation than is phase-comparison relaying. Reference 6 describes a host of things that tend to fool such ground relays. However, conventional directional-comparison-relaying equipments have certain features, developed as a result of experience, that minimize any tendency toward misoperation. Such features are: (1) limited sensitivity, (2) slight time delay in auxiliary relays, and (3) "transient blocking" or the prolongation of a carrier-current blocking signal for several cycles after a relay operates to try to shut it off. Also, induction-type directional units in both the carrier-starting and the tripping functions make the units unresponsive to transients in only one of the operating quantities.

Ground distance relays, that respond to positive-phase-sequence impedance, for controlling carrier-current transmission and for tripping eliminate the problem of misoperation on transients.

COMBINED PHASE AND DIRECTIONAL COMPARISON

Directional-comparison relaying using directional-ground relays may operate undesirably if there is sufficient mutual induction with a neighboring power circuit.[6] The directional-ground relays misoperate because their polarization is adversely affected, as will be described later. This would seem to indicate the desirability of phase-comparison relaying which would be unaffected by mutual induction. If phase comparison was completely applicable, it would be a good solution. However, occasionally it does not have sufficient sensitivity for phase faults, although it would be entirely satisfactory for ground faults. Under these circumstances combined phase- and directional-comparison relaying is chosen. The directional-comparison principle is used for phase faults and the phase-comparison principle is used for ground faults. Because the carrier-current transmitter and receiver are employed in common, the equipment is only a little more expensive than directional comparison alone. Incidentally, the phase-comparison ground-fault equipment is less affected by most of the transient conditions that affect directional-ground relays.

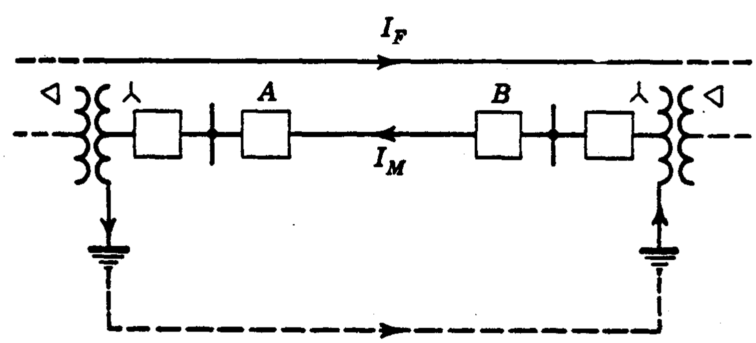


Fig. 15. Illustrating the cause of undesired directional-ground-relay operation resulting from mutual induction.

If ground distance relays were used in the directional-comparison equipment instead of directional-ground relays, it would be unnecessary to resort to combined phase- and directional-comparison equipment. However, it would be somewhat more expensive, but it would provide better back-up protection.

THE EFFECT OF MUTUAL INDUCTION ON DIRECTIONAL-GROUND RELAYS

Figure 15 illustrates the fundamental principle involved in the undesired operation of directional-ground relays. As shown in Fig. 15, fault current I_F flowing in a nearby line causes current I_M to flow by mutual induction in the line under consideration. The induced current circulates through grounded-neutral power-transformer banks at the ends of the line and the earth, as shown. The difficulty is that directional-ground relays at both ends of the line tend to operate under such circumstances. At location *B*, the polarizing current flows from the ground into the neutral of the grounded power transformer and from the bus into the line; this is the same as for a ground fault on the line for which directional-ground relays are intended to operate. The fact that, at end *A*, both the currents are reversed with respect to the directions at *B* also produces a tripping tendency. The same operating tendencies would exist if the relays were voltage-polarized. In other words, the phase of the polarizing quantity is not independent of the direction of current flow in the line, as it is when a short circuit occurs in the line or beyond either end.

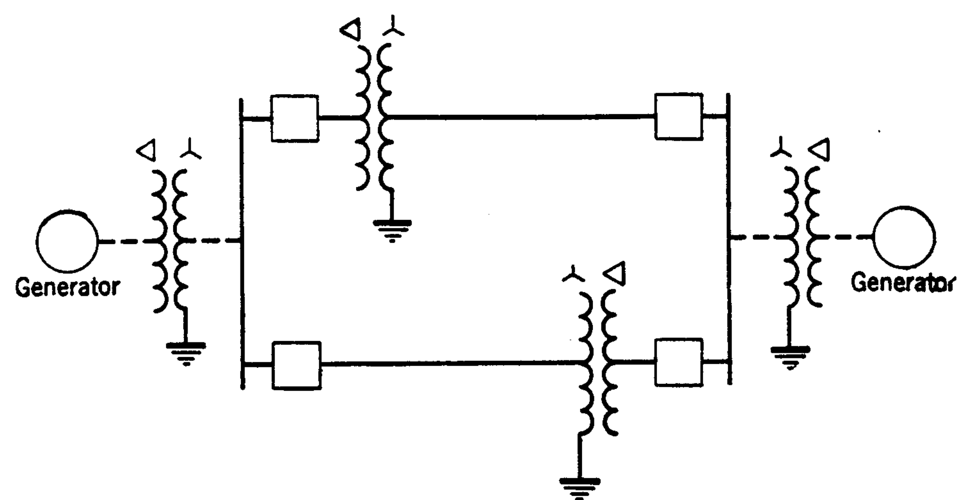
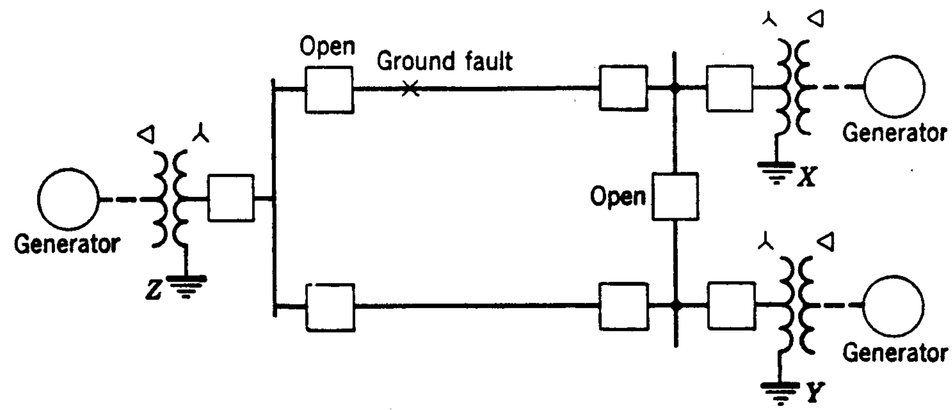


Fig. 16. Parallel circuits subject to mutual induction that are electrically independent so far as zero~phase-sequence currents are concerned.

One can immediately see the significance of the foregoing circumstances when directional-comparison pilot relaying is involved. Since the directional-ground relays at both ends of the circuit have a tripping tendency, if the induced current is high enough to pick up the relays, the circuit will be tripped undesirably.

The conditions of Fig. 15 are extreme in view of the fact that the line section in which induced current flows cannot directly contribute short-circuit current to the other circuit. However, it is not an impossible situation. It can exist whenever electrically independent circuits are closely paralleled, or in a case such as that illustrated in Fig. 16. Although these two circuits are paralleled at their ends, they are independent so far as zero-phase-sequence currents are concerned.



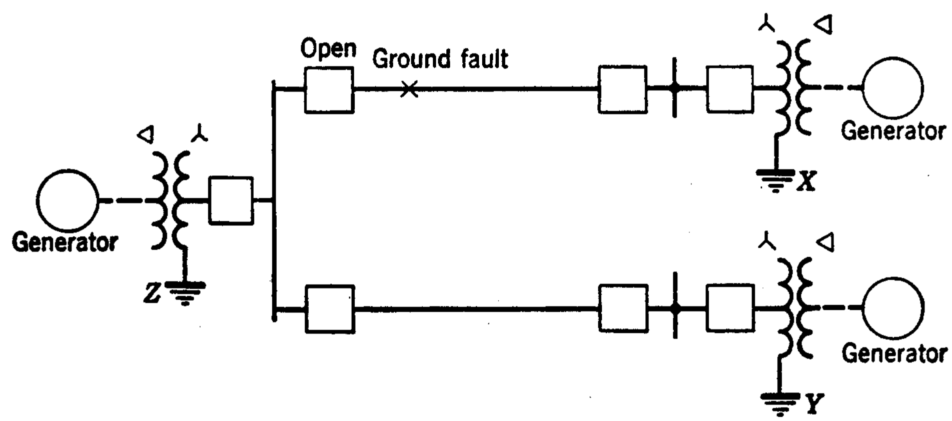


Fig. 17. Situations in which lines are directly paralleled at one end only.

Situations that are more apt to be encountered are illustrated in Fig. 17. It is only necessary in either case of Fig. 17 that the breaker of the faulty line be open at the end where the lines are normally paralleled, in order to have the condition that can produce an undesirable tripping tendency of the directional-ground relays of the sound line. This breaker may be open either because it was tripped by its protective relays immediately when the fault occurred and before the breaker at the other end could trip, or because the line had been open at both ends and the breaker at the other end was reclosed first on a persisting fault. Not only would the directional elements at both ends of the sound line permit tripping, but the current magnitudes may be large enough so that selectivity would not be obtained.

Sometimes it is even unnecessary that the breaker in the faulty line of Fig. 17 be open. If the effect of mutual induction is great enough, it can overcome the tendency of the unfaulted line to supply current to the fault, and actually reverse the direction of its current.

Apart from phase-comparison relaying or directional ground distance relays, other solutions to the problem can sometimes be found. The zero-phase-sequence current or voltage at the ends of the faulted circuit may be enough greater than at the corresponding ends of the unfaulted circuit so that a relay can be interposed that balances the corresponding quantities and permits only the circuit to trip that has the larger quantity. Another possible solution is to parallel the CT's in the neutrals of the power transformers, as, for example, at *X* and *Y* of Fig, 17, and to use the resulting current to polarize the directional relays of both lines at that end. At the other end of the circuits of Fig. 17, a CT in the neutral of the one power-transformer bank shown at *Z* would suffice for the directional-ground relays of both lines; or voltage polarization might be used at this end.

Should the line terminals be too far apart at one end, as when two lines run close to one another for part of their length and then diverge, it would be impossible to employ the alternatives to phase-comparison relaying that have been described. One remaining alternative would be to determine if the magnitude of the zero-phase-sequence current or voltage at the ends of the lines could not be used alone to permit operation, subject to directional control, only if the magnitude was high enough. Another possibility is to take advantage of the fact that the phase-to-neutral voltages of the circuit in which the induced current flows are usually not as low during the induced-current condition as they are while a ground fault exists on the line itself.

It was mentioned in Chapter 13 that a negative-phase-sequence directional-ground relay would not be affected by mutual induction. However, such a relay has other disadvantages, as mentioned also, that make it desirable to seek some other alternative.

ALL-ELECTRONIC DIRECTIONAL-COMPARISON EQUIPMENT

All-electronic directional-comparison equipment, including electronic phase distance and directional-ground relays, has been in service since 1953.[16] The average operating time of this equipment is $^5/_8$ cycle with a maximum of 1.0 cycle, as compared with 1.0 to 3.0 cycles for conventional electromechanical relay equipment.

Such operating speeds eventually become necessary, not only to maintain stability when faults occur but also to minimize the damage from ever-increasing concentrations of short-circuit current.

The application procedures and problems are the same as those described for the electromechanical equipment.

MICROWAVE

A microwave pilot is used for relaying only when the relaying equipment can share the channel with enough other services; it is not economically justifiable for relaying alone if carrier current or wire pilot is applicable.[17]

Microwave is entirely suitable although it is not as reliable as carrier current for protective-relaying purposes; this is partly because of the complex circuitry and the large number of tubes involved, and also because of the large number of services on the same microwave channel. When repeater stations are necessary, the complexity practically doubles with further loss of reliability. Of course, one realize that the requirements of protective relaying as to reliability are in certain respects more severe than the requirements of other services that use the microwave channel. Any lapse in the signal when a fault occurs is unacceptable.

Microwave has certain theoretical advantages over carrier current because it is dissociated from the power line,[18] but its only real advantage is in connection with remote tripping, which will be considered later. Occasionally, microwave is useful where the attenuation would be too high for carrier current, such as on a power-cable circuit, but even there microwave would probably not be selected unless there were many other uses in addition to protective relaying.

The same relaying equipments that are used with a carrier-current pilot are also used with a microwave pilot. Therefore, the application considerations are the same so far as the relaying equipment is concerned.

THE MICROWAVE CHANNEL

The microwave channel is a line-of-sight-radio system operating on a frequency band in the United States assigned by the Federal Communications Commission in the range from 950 to 30,000 megacycles.[19] Such a system requires that a straight line from one antenna to another be above intervening objects, preferably by about 50 feet. This usually limits the distance between antennae to about 20 to 50 miles, depending on the topography of the land. Where a longer channel is required, one or more "repeater stations" may be necessary. One repeater station doubles the base channel equipment, except that only one additional tower is necessary; hence, the cost of a microwave channel is dependent on its length.

It is the practice to use standby equipment automatically switched into service in the event that the regular equipment fails.

For protective relaying that cannot tolerate even a moment's outage when a fault occurs, operation from a power-system a-c source is not acceptable. It is necessary to provide an a-c generator operating from the station battery, or d-c-operated equipment. This becomes more of a problem at a repeater station where a suitable battery source would not otherwise be available.

For protective-relaying purposes, the practice is to modulate the microwave frequency directly by any of the usual methods, such as, for example, by a so-called "tone." Such a tone is a single-frequency voltage in the audio range or above. Tones above the audio range are preferred because the time constants of their filter circuits are shorter, and therefore it is unnecessary to delay tripping to allow time for the receiver output to build up sufficiently to block tripping.

REMOTE TRIPPING

The principal advantage of microwave for protective relaying is that the presence of a fault on the protected line will not interfere with the transmission of a remote-tripping signal. For the protection of three-terminal lines, there are circumstances when the relays at a given terminal cannot operate to trip their breakers until after the breakers trip at another terminal. With microwave, the first relays to operate can cause the transmission of a tripping signal to another terminal and thereby eliminate part of the time delay in the sequential tripping of this other terminal.[20]

This ability to perform remote tripping without hindrance by a fault makes possible the use of a different principle for line protection.[18] To apply this principle, it is first necessary that the high zones of the relays at all terminals overlap for all types of fault in such a way that, for any fault, the relays of at least one terminal will always operate at high speed. Then, if each terminal is arranged to transmit a trip signal to each other terminal, practically simultaneous high-speed tripping will occur at all terminals; the remote tripping will be delayed about 2 to 3 cycles. Of course, each terminal is still free to trip at high speed independently of the remote-tripping equipment whenever a fault occurs within that terminal's high-speed-tripping zone. This principle eliminates the need for blocking relays, as required by directional comparison, but it often requires distance relays for phase- and ground-fault protection. Where remote tripping is required for multi terminal applications, this type of relaying would have its greatest application; otherwise, the added time delay for certain faults would discourage its general usage where simultaneous high-speed tripping is possible with directional comparison.

Incidentally, the foregoing principle can be applied to a wire-pilot system by the use of tones.

HIGH-SPEED RECLOSING

High-speed automatic reclosing of transmission-line breakers after they have tripped to clear a fault is generally possible only with pilot relaying, because only pilot relaying is able to cause all line terminals to trip at high speed and practically simultaneously. With such high-speed tripping and reclosing, generators do not have time to swing very far out of phase, and therefore no synchronism check is necessary before reclosing. The experience with such high-speed reclosing (or "ultra-high-speed reclosing," as it is sometimes called) has been excellent,[21]

Generally, all three phases are tripped and reclosed for any kind of fault. Infrequently, however, such three-phase switching cannot be used, but it is possible to use single-phase switching to advantage.[22] Such a possibility exists when there is only one line connecting a hydroelectric generating station to its system. If about 25% or more of the load on the generating station is dropped when a line is tripped, the generators will speed up too rapidly to permit high-speed reclosing. But for single-phase-to-ground faults, if only the faulty phase is tripped and reclosed, stability can often be maintained; for any other kind of fault, all three phases are tripped but are not reclosed. Single-phase switching can be performed with conventional relaying equipment by the addition of "phase-selector" relays.[23]

High-speed reclosing is permitted only when high-speed tripping is caused by the operation of the pilot equipment or the first-zone units of distance relays. When tripping is caused by any other units, automatic reclosing is blocked until released locally by an operator or remotely by supervisory control.

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REVIEW PROBLEMS

1. A system short-circuit study is to be made. What quantities should be obtained for studying the application of protective relays? What other data are required to apply (*a*) overcurrent relays, (*b*) pilot relays, and (*c*) distance relays?

2. Name and describe briefly the various methods for obtaining selectivity.

3. Discuss the factors governing the choice of transmission-line-relaying equipment. Which type would lend itself best to standardization, and why?

4. Given a breaker with 1200/5 bushing CT's having the secondary-excitation characteristic of Fig. 3 of Chapter 7. What would the ASA accuracy classification be for the 40-turn tap (ratio 200/5)? Assume the tap winding to be fully distributed..

5. On what basis is it permissible to superimpose system and relay characteristics on the same *R-X* diagram for the purpose of studying relay response?

6. Under what circumstance is distance relaying affected by short-circuit-current magnitude?

7. Show the complete CT and relay connections for applying percentage-differential protection to the power transformer of Fig. 18. Draw the three-phase voltage vector diagrams for both sides of the power transformer.

8. Discuss the virtues of high-speed relaying.

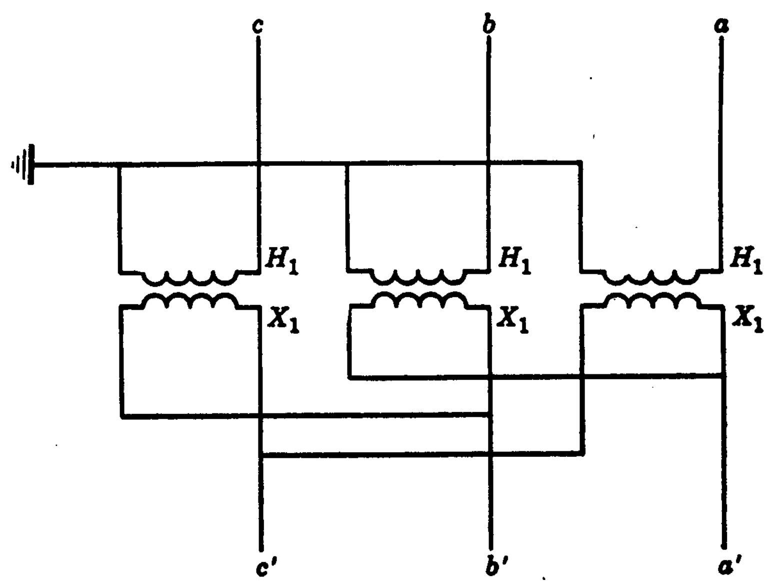

Fig. 18. Illustration for Review Problem 7.

9. Write "true" or "false" after each of the following:

(*a*) Overcurrent relays with more-inverse curves are better to use when the generating capacity changes more from time to time.

(*b*) Instantaneous overcurrent relays are more applicable on the longer lines.

(*c*) Mho-type distance relays are more 1ikely to operate undesirably on power swings than other types of distance relays.

(*d*) Any distance relay–no matter where it is located–will trip on loss of synchronism.

(*e*) Sensitive, high-speed bus protection can always be obtained with differentially connected overcurrent relays.

(*f*) In attended stations, it is not the practice to let transformer overload relays trip the transformer breakers.

(*g*) Back-up relaying is not a substitute for good maintenance.