6 CARRIER-CURRENT-PILOT AND MICROWAVE-PILOT RELAYS

Chapter 5 introduced the subject of pilot relaying, gave the fundamental principles involved, and described some typical wire-pilot relaying equipments. In this chapter, we shall deal with carrier-current-pilot and microwave-pilot relaying; for either type of pilot, the relay equipment is the same. Two types of relay equipment will be described, the "phase-comparison" type, which is much like the a-c wire-pilot types, and the "directional-comparison" type, which is similar to the d-c wire-pilot types.

THE CARRIER-CURRENT PILOT

It is not necessary for one to understand the details of carrier-current transmitters or receivers in order to understand the fundamental relaying principles. All one needs to know is that when a voltage of positive polarity is impressed on the control circuit of the transmitter, it generates a high-frequency output voltage. In the United States, the frequency range allotted for this purpose is 30 to 200 kc. This output voltage is impressed between one phase conductor of the transmission line and the earth, as shown schematically in Fig. 1.

Each carrier-current receiver receives carrier current from its local transmitter as well as from the transmitter at the other end of the line. In effect, the receiver converts the received carrier current into a d-c voltage that can be used in a relay or other circuit to perform any desired function. This voltage is zero when carrier current is not being received.

"Line traps" shown in Fig. 1 are parallel resonant circuits having negligible impedance to power-frequency currents, but having very high impedance to carrier-frequency currents. Traps are used to keep the carrier currents in the desired channel so as to avoid interference with or from other adjacent carrier-current channels, and also to avoid loss of the carrier-current signal in adjoining power circuits for any reason whatsoever, external short circuits being a principal reason. Consequently, carrier current can flow only along the line section between the traps.
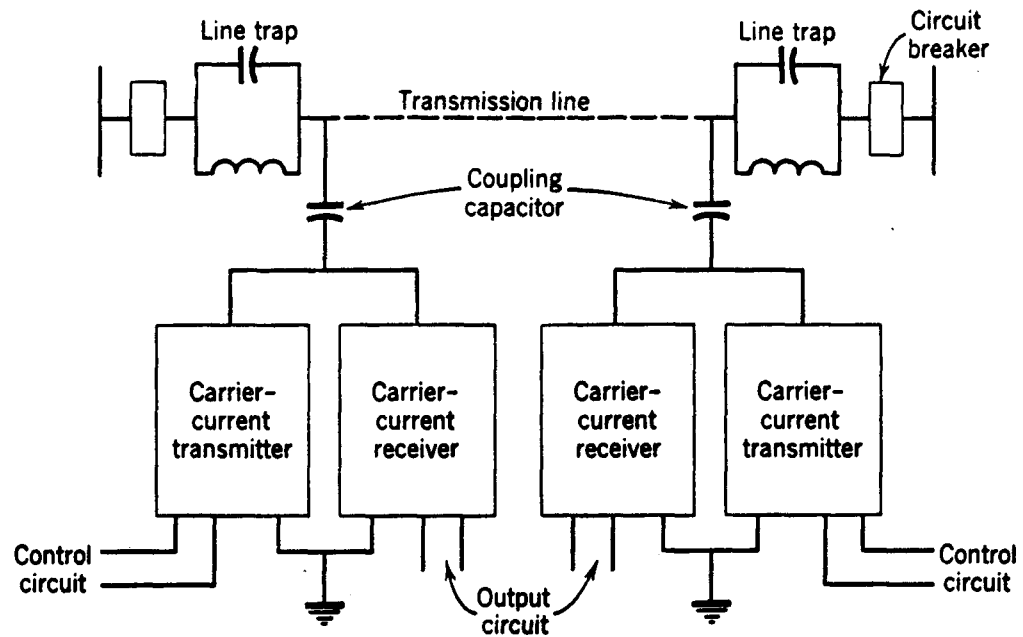
Fig. 1. Schematic illustration of the carrier-current-pilot channel.

THE MICROWAVE PILOT

The microwave pilot is an ultra-high-frequency radio system operating in allotted bands above 900 megacycles in the United States. The transmitters are controlled in the same manner as carrier-current transmitters, and the receivers convert the received signals into d-c voltage as carrier-current receivers do. With the microwave pilot, line coupling and trapping are eliminated, and, instead, line-of-sight antenna equipment is required.

The following descriptions of the relaying equipments assume a carrier-current pilot, but the relay equipment and its operation would be the same if a microwave pilot were used.

PHASE-COMPARISON RELAYING

Phase-comparison relaying equipment uses its pilot to compare the phase relation between current entering one terminal of a transmission-line section and leaving another. The current magnitudes are not compared. Phase-comparison relaying provides only primary protection; back-up protection must be provided by supplementary relaying equipment.

Figure 2 shows schematically the principal elements of the equipment at both ends of a two-terminal transmission line, using a carrier-current-pilot. As in a-c wire-pilot relaying, the transmission-line current transformers feed a network that transforms the CT output currents into a single-phase sinusoidal output voltage. This voltage is applied to a carrier-current transmitter and to a "comparer." The output of a carrier-current receiver is also
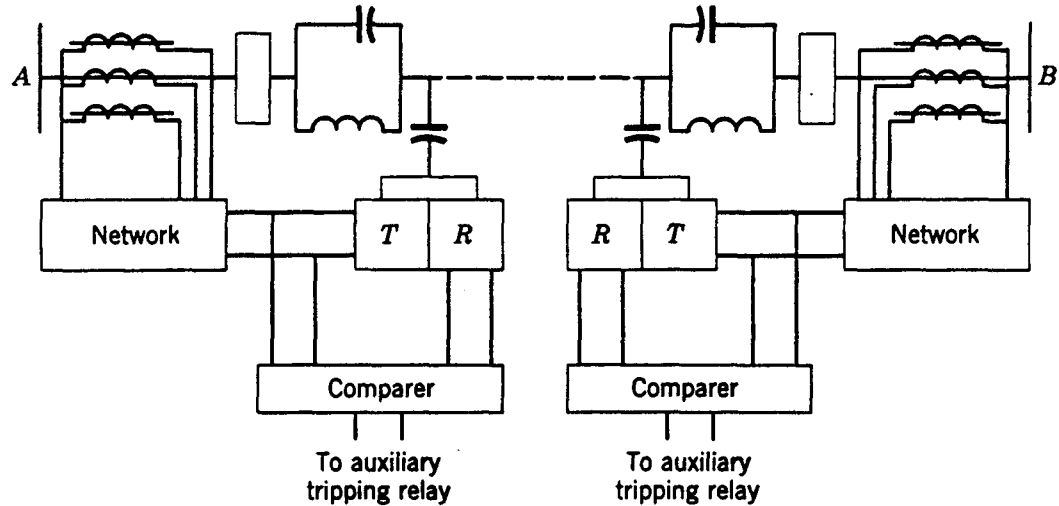

Fig. 2. Schematic representation of phase-comparison carrier-current-pilot equipment.
T = carrier-current transmitter; R ~ carrier-current receiver.

applied to the comparer. The comparer controls the operation of an auxiliary relay for tripping the transmission-line circuit breaker. These elements provide means for transmitting and receiving carrier-current signals for comparing at each end the relative phase relations of the transmission-line currents at both ends of the line.

Let us examine the relations between the network output voltages at both ends of the line and also the carrier-current signals that are transmitted during external and internal fault conditions. These relations are shown in Fig. 3. It will be observed that for an external fault at D, the network output voltages at stations A and B (waves a and c) are 180° out of phase; this is because the current-transformer connections at the two stations are reversed. Since an a-c voltage is used to control the transmitter, carrier current is transmitted only during the half cycles of the voltage wave when the polarity is positive. The carrier-current signals transmitted from A and B (waves b and d) are displaced in time, so that there is always a carrier-current signal being sent from one end or the other. However, for the internal fault at C, owing to the reversal of the network output voltage at station B caused by the reversal of the power-line currents there, the carrier-current signals (waves b and f) are concurrent, and there is no signal from either station every other half cycle.
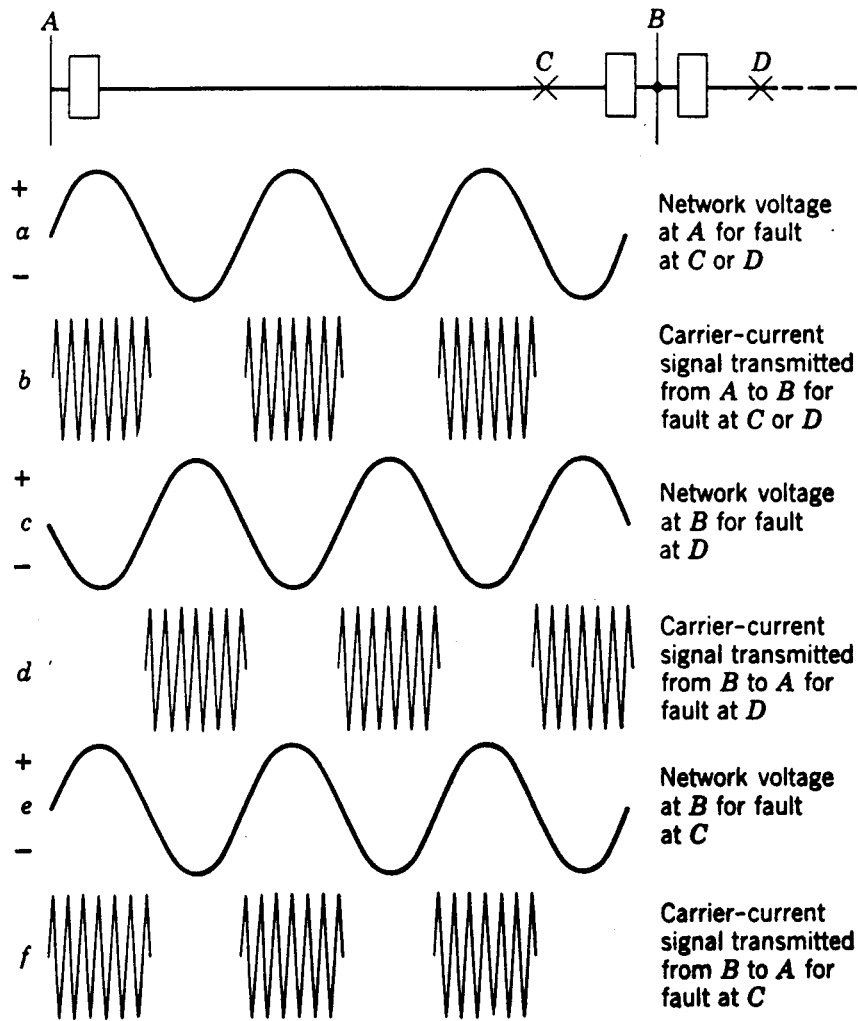
Fig. 3. Relations between network output voltages and carrier-current signals.

Phase-comparison relaying acts to block tripping at both terminals whenever the carrier-current signals are displaced in time so that there is little or no time interval when a signal is not being transmitted from one end or the other. When the carrier-current signals are approximately concurrent, tripping will occur wherever there is sufficient short-circuit current flowing. This is illustrated in Fig. 4 where the network output voltages are superimposed, and the related tripping and blocking tendencies are shown. As indicated in Figs. 3 and 4, the equipment at one station transmits a blocking carrier-current signal during one half cycle, and then stops transmitting and tries to trip during the next half cycle; if carrier current is not received from the other end of the line during this half cycle, the equipment operates to trip its breaker. But, if carrier current is received from the other end of the line during the interval when the local carrier-current transmitter is idle, tripping does not occur.
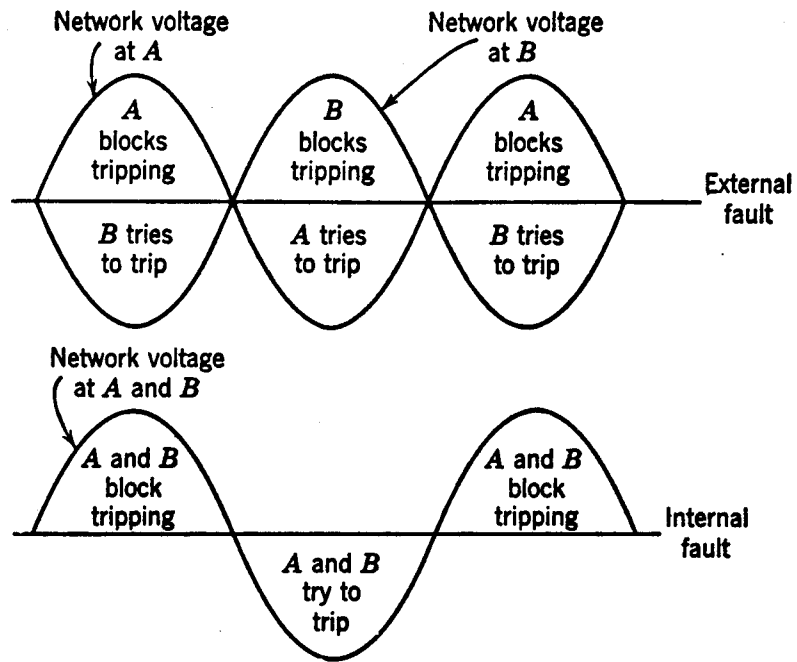
Fig. 4. Relation of tripping and blocking tendencies to network output voltages.

The heart of the phase-comparison system lies in what is sometimes called the "comparer." The comparer of one type of relaying equipment, shown schematically in Fig. 5, is a vacuum-tube equipment at each end of the line, which is here represented as a single tube.
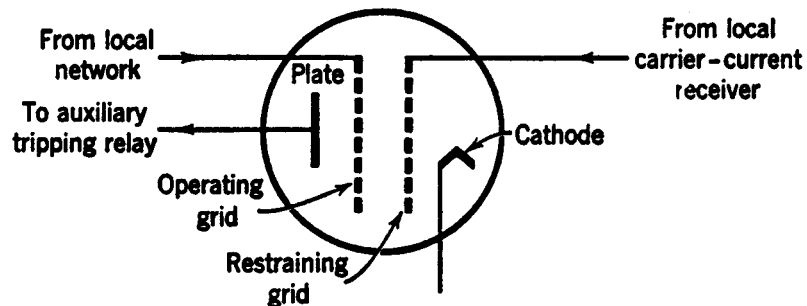

Fig. 5. Schematic representation of the comparer.

When voltage of positive polarity is impressed on the "operating" grid by the local network, the tube conducts if voltage of negative polarity is not concurrently impressed on the "restraining" grid by the local carrier-current receiver by virtue of carrier current received from the other end of the line. When the tube conducts, an auxiliary tripping relay picks up and trips the local breaker. Positive polarity is impressed on the operating grid of the local comparer during the negative half cycle of the network output of Fig. 3 when the local transmitter is idle. Therefore, the local transmitter cannot block local tripping. The voltage from the carrier-current receiver impressed on the restraining grid makes the tube non-conducting, whether the operating grid is energized or not, whenever carrier current is being received.

It is not necessary that the carrier-current signals be exactly interspersed to block tripping, nor must they be exactly concurrent to permit tripping. For blocking purposes, a phase shift of the order of 35° either way from the exactly interspersed relation can be tolerated. Considerably more phase shift can be tolerated for tripping purposes. It is necessary that more phase shift be permissible for tripping purposes because more phase shift is possible under tripping conditions than under blocking conditions. Phase shift under blocking conditions (i.e., when an external fault occurs) is caused by the small angular difference between the currents at the ends of the line, owing to the line-charging component of current, and also by the length of time it takes for the carrier-current signal to travel from one end of the line to the other, which is approximately at the speed of light. In a 60-cycle system, this travel time accounts for about 12° phase shift per 100 miles of line; it can be compensated for by shifting the phase of the voltage supplied by the network to the comparer by the same amount. No compensation can be provided for the charging-current effect, but this phase shift is negligible except with very long lines. The major part of the phase shift under tripping conditions (i.e., when an internal fault occurs) is caused by the generated voltages beyond the ends of the line being out of phase, and also by a different distribution of ground-fault currents between the two ends as compared with the distribution of phase-fault currents (as, for example, if the main source of generation is at one end of the line and the main ground-current source is at the other end); in addition, the travel time of the carrier-current signal is also a factor.

The principle of different levels of blocking and tripping sensitivity, described in connection with d-c wire-pilot relaying, applies also to phase-comparison pilot relaying. So-called "fault detectors," which may be overcurrent or distance relays, are employed to establish these two sensitivity levels. It is desirable that carrier current not be transmitted under normal conditions, to conserve the life of the vacuum tubes, and also to make the pilot available for other uses when not required by the relaying equipment. Consequently, one set of fault detectors is adjusted to pick up somewhat above maximum load current, to permit the transmission of carrier current. The other set of fault detectors picks up at still higher current, to permit tripping if called for by the comparer. The required pickup adjustment of these tripping fault detectors might be considerably higher for tapped-line applications; this will be treated in more detail when we consider the application of relays for transmission-line protection. Tripping for an internal fault will occur only at the ends of a line where sufficient shortcircuit current flows to pick up the tripping fault detectors.

It will be evident from the foregoing that the phase-comparison pilot is a blocking pilot, since a pilot signal is not required to permit tripping. Without the agency of the pilot, phase-comparison relaying reverts to high-speed non-directional overcurrent relaying. Failure of the pilot will not prevent tripping, but tripping will not be selective under such circumstances; that is, undesired tripping may occur. A short circuit on the protected line between ground and the conductor to which the carrier-current equipment is coupled will not interfere with desired tripping, because carrier-current transmission is not required to permit tripping; external faults, being on the other side of a line trap, will not affect the proper transmission of carrier current when it is required.

Phase-comparison relaying is inherently immune to the effects of power surges or loss of synchronism between sources of generation beyond the ends of a protected line. Similarly, currents flowing in a line because of mutual induction from another nearby circuit will not affect the operation of the equipment. In both of these situations, the currents merely flow through the line as to an external load or to an external short circuit.

DIRECTIONAL-COMPARISON RELAYING

Modern relaying equipment of the directional-comparison type operates in conjunction with distance relays because the distance relays will provide back-up protection, and because certain elements of the distance relays can be used in common with the directional-comparison equipment. However, for our immediate purposes, we shall consider only those elements that are essential to directional-comparison relaying.

With directional-comparison relaying, the pilot informs the equipment at one end of the line how a directional relay at the other end responds to a short circuit. Normally, no pilot signal is transmitted from any terminal. Should a short circuit occur in an immediately adjacent line section, a pilot signal is transmitted from any terminal where short-circuit current flows out of the line (i.e., in the non-tripping direction). While any station is transmitting a pilot signal, tripping is blocked at all other stations. But should a short circuit occur on the protected line, no pilot signal is transmitted and tripping occurs at any terminal where short-circuit current flows. Therefore, the pilot is a blocking pilot, since the reception of a pilot signal is not required to permit tripping.
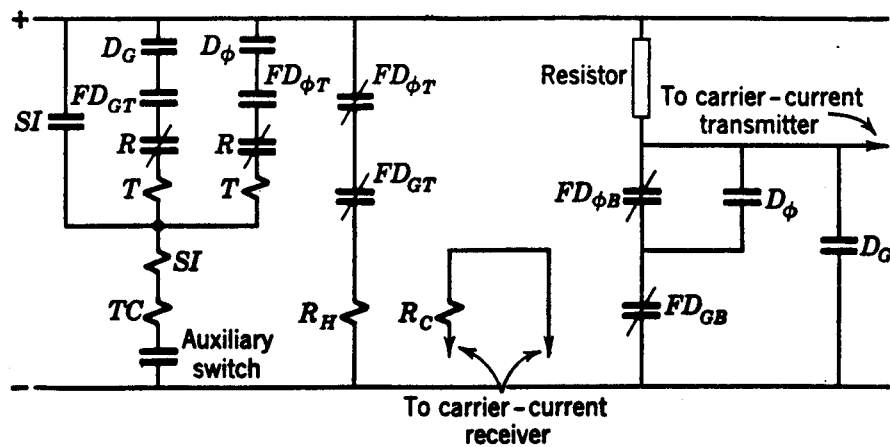

Fig. 6. Schematic diagram of essential contact circuits of directional-comparison relaying equipment. SI = seal-in relay; D_G = directional ground relay; D_ϕ = directional phase relay; FD_{GT} = ground tripping fault-detector relay; $FD_{\phi T}$ = phase tripping fault-detector relay; R = receiver relay; R_H = d-c holding coil; R_C = carrier-current coil; T = target; TC = trip coil; FD_{GB} = ground blocking fault-detector relay; $FD_{\phi B}$ = phase blocking fault-detector relay.

The pilot signal is steady once it is started, and not every other half cycle as in phase-comparison relaying.

The essential relay elements at each end of a line are shown schematically in Fig. 6 for one type of equipment. With two exceptions, all the contacts are shown in the position that they take under normal conditions; the exceptions are that the receiver-relay contacts (R) are open because the receiver-relay holding coil (R_H) is energized normally, and the

circuit-breaker auxiliary switch is closed when the breaker is closed. The phase directional-relay contacts (D_ϕ) may be closed or not, depending on the direction in which load current is flowing.

Now, let us assume that a short circuit occurs in an adjoining line back of the end where the equipment of Fig. 6 is located. If the magnitude of the short-circuit current is high enough to operate a blocking fault detector ($FD_{\phi B}$ for a phase fault or FD_{GB} for a ground fault), the operation of this fault detector opens the connection from the negative side of the d-c bus to the control circuit of the carrier-current transmitter. The polarity of this connection then becomes positive, owing to the connection through the resistor to the positive side of the d-c bus, and the carrier-current transmitter transmits a signal to block tripping at the other terminals of the line. There is no tendency to trip at this terminal because the current is flowing in the direction to open the directional-relay contacts (D_G or D_ϕ) in the tripping circuit, even though a tripping fault detector (FD_{GT} or $FD_{\phi T}$) may have operated. Moreover, the receiver relay contacts (R) will have stayed open because the coil R_C was energized by the carrier-current receiver at about the same instant that the coil R_H was de-energized by the opening of the "b" contact of FD_{GT} or $FD_{\phi T}$. At each of the other terminals of the line where the current is flowing into the line, the operation will have been similar, except that, depending on the type of fault, a directional relay will have closed its contacts. However, tripping will have been blocked by receipt of the carrier-current signal, the contacts (R) of the receiver relay having been held open as described for the first terminal. The tripping fault detectors may or may not have picked up since they are less sensitive than the blocking fault detectors, but tripping would have been blocked in any event. The operation of a blocking fault detector at one of these other terminals may have started carrier transmission from that terminal, but it would have been immediately stopped by the operation of a directional relay.

For a short circuit on the protected line, the directional relays at all terminals where short-circuit current flows will close their contacts, thereby stopping carrier transmission as soon as it is started by the blocking fault detectors. With no carrier signal to block tripping, all terminals will trip where there is sufficient fault current to pick up a tripping fault detector.

The directional-ground relay can stop carrier-current transmission whether it was started by either the phase blocking fault detector or the ground blocking fault detector, but the directional phase relay can stop transmission only if it was started by the phase blocking fault detector. This illustrates how "ground preference" is obtained if desired. The principle of ground preference is used when a directional phase relay is apt to operate incorrectly for a ground fault. Ground preference is not required if distance-type phase-fault detectors are used.

Figure 6 shows only the contacts of the phase relays of one phase. In the tripping and carrier-stopping circuits, the contact circuits for the other two phases would be in parallel with those shown. In the receiver-relay d-c holding-coil circuit and in the carrier-starting circuit, the contacts would be in series.

A feature that contributes to high-speed operation is the "normally blocked trip circuit." As shown in Fig. 6, this feature consists of providing the carrier-current receiver relay with a second coil (R_H), which, when energized, holds the receiver-relay contact open as when carrier current is being received. This auxiliary coil is normally energized through a series circuit consisting of a "b" contact on each tripping fault-detector relay. In earlier

equipments without the normally blocked trip circuit, the reception of carrier current had to open the receiver-relay "*b*" contact before a tripping fault detector could close its "*a*" contact, and this race required a certain time delay in the tripping-fault-detector operation to avoid undesired tripping. With the normally blocked trip circuit, the receiver-relay contact is held open normally by the R_H coil; and, when a fault occurs, carrier-current transmission is started and the R_C coil is energized at approximately the same time that the R_H coil is de-energized. Thus, the flux keeping the relay picked up does not have time to change. Therefore, the tripping fault detector can be as fast as possible, and there is no objectionable contact race.

The term "intermittent," as contrasted with "continuous," identifies a type of pilot in which the transmission of a pilot signal occurs only when short circuits occur. A continuous-type pilot would not require the normally blocked trip circuit, but it would have the same disadvantage as a tripping pilot because there would be no way to stop the transmission of the pilot signal at a station where the breaker was closed and where there was no flow of short-circuit current for an internal fault. Therefore, it is evident that the directional-comparison pilot is of the intermittent type. As such, it has the same desirable features, described for the phase-comparison pilot, of conserving the life of vacuum tubes and of permitting other uses to be made of the pilot when not required by the relaying equipment.

The blocking-fault-detector function may be directional or not, but the tripping-fault-detector function must be directional. In other words, a carrier signal may be started at a given station whenever a short circuit occurs either in the protected line or beyond its ends, and may then be stopped immediately if the current at that station is in the tripping direction; or the carrier signal may be started only if the current is in the non-tripping direction. The phase-fault detectors are distance-type relays. When mho-type distance relays are used, the directional function is inherently provided, and the separate directional relays of Fig. 6 are not required. Overcurrent and directional relays are used for ground-fault detectors.

Directional-comparison relaying requires supplementary equipment to prevent tripping during severe power surges or when loss of synchronism occurs. In a later chapter we shall see what loss of synchronism "looks" like to protective relays, and how it is possible to differentiate between such a condition and a short circuit.

The ground-relaying portion of directional-comparison equipment is apt to cause undesired tripping because of mutual induction during ground faults on certain arrangements of closely paralleled power lines. The remedy for this tendency is described in a later chapter where the effects of mutual induction are described.

LOOKING AHEAD

We have now completed our examination of the operating principles and characteristics of several types of commonly used protective-relaying equipments. Much more could have been said of present-day relays that might be helpful to one who intends to pursue this subject further. However, an attempt has been made to present the essential information as briefly as possible so as not to interfere with the continuity of the material. There are many more types of protective relays, some of which will be described later in connection

with specific applications. However, these are merely those basic types that we have considered, but arranged in a slightly different way.

We are not yet ready to study the application of the various relays. We have learned how various relay types react to the quantities that actuate them. We must still know how to derive these actuating quantities and how they vary under different system-operating conditions. If one is able to ascertain the difference in these quantities between a condition for which relay operation is required and all other possible conditions for which a relay must not operate, he can then employ a particular relay, or a combination of relays with certain connections, that also can recognize the difference and operate accordingly.

Because protective relays receive their actuating quantities through the medium of current and voltage transformers, and because the connections and characteristics of these transformers have an important bearing on the response of protective relays, these transformers will be our next consideration.

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