5 WIRE-PILOT RELAYS

Pilot relaying is an adaptation of the principles of differential relaying for the protection of transmission-line sections. Differential relaying of the type described in Chapter 3 is not used for transmission-line protection because the terminals of a line are separated by too great a distance to interconnect the CT secondaries in the manner described. Pilot relaying provides primary protection only; back-up protection must be provided by supplementary relaying.

The term "pilot" means that between the ends of the transmission line there is an interconnecting channel of some sort over which information can be conveyed. Three different types of such a channel are presently in use, and they are called "wire pilot," "carrier-current pilot," and "microwave pilot." A wire pilot consists generally of a two-wire circuit of the telephone-line type, either open wire or cable; frequently, such circuits are rented from the local telephone company. A carrier-current pilot for protective-relaying purposes is one in which low-voltage, high-frequency (30 kc to 200 kc) currents are transmitted along a conductor of a power line to a receiver at the other end, the earth and ground wire generally acting as the return conductor. A microwave pilot is an ultra-high-frequency radio system operating above 900 megacycles. A wire pilot is generally economical for distances up to 5 or 10 miles, beyond which a carrier-current pilot usually becomes more economical. Microwave pilots are used when the number of services requiring pilot channels exceeds the technical or economic capabilities of carrier current.

In the following, we shall first examine the fundamental principles of pilot relaying, and then see how these apply to some actual wire-pilot relaying equipments.

WHY CURRENT-DIFFERENTIAL RELAYING IS NOT USED

Because the current-differential relays described in Chapter 3 for the protection of generators, transformers, busses, etc., are so selective, one might wonder why they are not used also for transmission-line relaying. The principal reason is that there would have to be too many interconnections between current transformers (CT's) to make current-differential relaying economically feasible over the usual distances involved in transmission-line relaying. For a three-phase line, six pilot conductors would be required, one for each phase CT and one for the neutral connection, and two for the trip circuit. Because even a two-wire pilot much more than 5 to 10 miles long becomes more costly than a carrier-current pilot, we could conclude that, on this basis alone, current-differential relaying with six pilot wires would be limited to very short lines.

Other reasons for not using current-differential relaying like that described in Chapter 3 are: (1) the likelihood of improper operation owing to CT inaccuracies under the heavy loadings that would be involved, (2) the effect of charging current between the pilot wires, (3) the large voltage drops in the pilot wires requiring better insulation, and (4) the pilot currents and voltages would be excessive for pilot circuits rented from a telephone company. Consequently, although the fundamental principles of current-differential relaying will still apply, we must take a different approach to the problem.

PURPOSE OF A PILOT

Figure 1 is a one-line diagram of a transmission-line section connecting stations *A* and *B*, and showing a portion of an adjoining line section beyond B. Assume that you were at station *A*, where very accurate meters were available for reading voltage, current, and the phase angle between them for the line section *AB*. Knowing the impedance characteristics per unit length of the line, and the distance from *A* to *B*, you could, like a distance relay, tell the difference between a short circuit at *C* in the middle of the line and at *D*, the far end of the line. But you could not possibly distinguish between a fault at *D* and a fault at *E* just beyond the breaker of the adjoining line section, because the impedance between *D* and *E* would be so small as to produce a negligible difference in the quantities that you were measuring. Even though you might detect a slight difference, you could not be sure how much of it was owing to inaccuracies, though slight, in your meters or in the current and voltage transformers supplying your meters. And certainly, you would have difficulties if offset current waves were involved. Under such circumstances, you would hardly wish to accept the responsibility of tripping your circuit breaker for the fault at *D* and not tripping it for the fault at *E*.

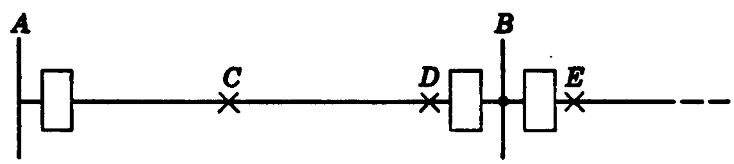

Fig. 1. Transmission-line sections for illustrating the purpose of a pilot.

But, if you were at station *B*, in spite of errors in your meters or source of supply, or whether there were offset waves, you could determine positively whether the fault was at *D* or *E*. There would be practically a complete reversal in the currents, or, in other words, approximately a 180° phase-angle difference.

What is needed at station *A*, therefore, is some sort of indication when the phase angle of the current at station *B* (with respect to the current at *A*) is different by approximately 180° from its value for faults in the line section *A B*. The same need exists at station *B* for faults on either side of station *A*. This information can be provided either by providing each station with an appropriate sample of the actual currents at the other station, or by a signal from the other station when its current phase angle is approximately 180° different from that for a fault in the line section being protected.

TRIPPING AND BLOCKING PILOTS

Having established that the purpose of a pilot is to convey certain information from one end of a line section to another in order to make selective tripping possible, the next consideration is the use to be made of the information. If the relaying equipment at one end of the line must receive a certain signal or current sample from the other end in order to prevent tripping at the one end, the pilot is said to be a “blocking” pilot. However, if one end cannot trip without receiving a certain signal or current sample from the other end, the pilot is said to be a “tripping” pilot. In general, if a pilot-relaying equipment at one end of a line can trip for a fault in the line with the breaker at the other end closed, but with no current flowing at that other end, it is a blocking pilot–otherwise it is like a tripping pilot.

It is probably evident from the foregoing that a blocking pilot is the preferred–if not the required–type. Other advantages of the blocking pilot will be given later.

D-C WIRE-PILOT RELAYING

Scores of different wire-pilot-relaying equipments have been devised and many are in use today, where d-c signals in one form or another have been transmitted over pilot wires, or where pilot wires have constituted an extended contact-circuit interconnection between relaying equipments at terminal stations. For certain applications, some such arrangement has advantages particularly where the distances are short and where a line may be tapped to other stations at one or more points. However, d-c wire-pilot relaying is nearly obsolete for other than very special applications. Nevertheless, a study of this type will reveal certain fundamental requirements that apply to modern pilot-relaying equipments, and will serve to prepare us better for understanding still other fundamentals.

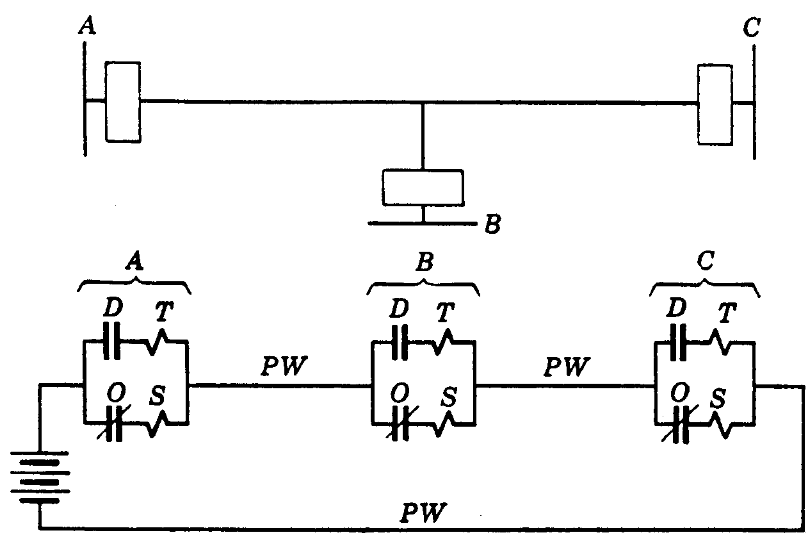

Fig. 2. Schematic illustration of a d-c wire-pilot relaying equipment. *D* = voltage-restrained directional (mho) relay; *O* = overcurrent relay; *T* = auxiliary tripping relay; *S* = auxiliary supervising relay; *PW* = pilot wire.

An example of d-c wire-pilot relaying is shown very schematically in Fig. 2. The relaying equipments at the three stations are connected in a series circuit, including the pilot wires and a battery at station *A*. Normally, the battery causes current to flow through the "*b*" contacts of the overcurrent relay and the coil of the supervising relay at each station. Should a short circuit occur in the transmission-line section, the overcurrent relay will open its "*b*" contact at any station where there is a flow of short-circuit current. If the short-circuit-current flow at a given station is into the line, the directional relay at that station will close its "*a*" contact. The circuit at this station is thereby shifted to include the auxiliary tripping relay instead of the supervising relay. If this occurs at the other stations, current will flow through the tripping auxiliaries at all stations, and the breakers at all the line terminals will trip. But should a fault occur external to the protected-line section, the

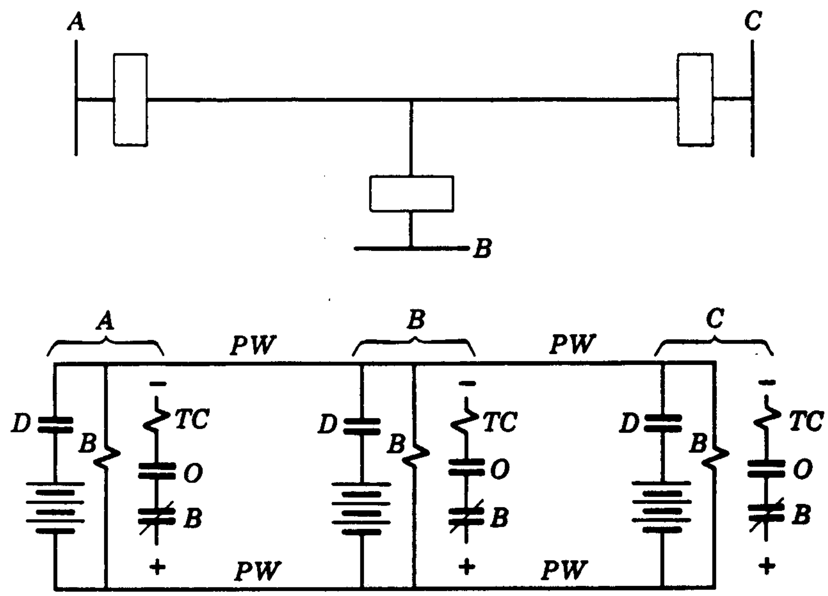

Fig. 3. Schematic illustration of a d-c wire-pilot scheme where information is transmitted over the pilot. *D* = voltage-restrained directional (mho) relay; *B* = auxiliary blocking relay; *O* = overcurrent relay; *TC* = trip coil; *PW* = pilot wire.

overcurrent relay at the station nearest the fault will pick up, but the directional relay will not close its contact because of the direction of current flow, and the circuit will be open at that point, thereby preventing tripping at the other stations. If an internal fault occurs for which there may be no short-circuit-current flow at one of the stations, the overcurrent relay at that station will not pick up; but pilot-wire current will flow through the supervising auxiliary relay (whose resistance is equal to that of the tripping auxiliary relay), and tripping will still occur at the other two stations. (The supervising relays not only provide a path for current to flow so that tripping will occur as just described but also can be used to actuate an alarm should the pilot wires become open circuited or short circuited.) Therefore, this arrangement has the characteristics of a blocking pilot where the blocking signal is an interruption of current flow in the pilot. However, if the overcurrent and the supervising relays were removed from the circuit, it would be a tripping pilot, because tripping could not occur at any station unless all the directional relays operated to close their contacts, and tripping would be impossible if there was no flow of short-circuit current into one end.

An example of a blocking pilot, where positive blocking information is transmitted by the pilot, is shown in Fig. 3. Here, the directional relay at each station is arranged to close its contact when short-circuit current flows out of the line as to an external fault. It can be seen that, for an external fault beyond any station, the closing of the directional-relay contact at that station will cause a d-c voltage to be impressed on the pilot that will pick up the blocking relay at each station. The opening of the blocking relay "*b*" contact in series with the trip circuit will prevent tripping at each station. For an internal fault, no directional relay will operate, and hence no blocking relay will pick up, and tripping will occur at all stations where there is sufficient short-circuit current flowing to pick up the overcurrent relay.

ADDITIONAL FUNDAMENTAL CONSIDERATIONS

Now that we are a little better acquainted with pilot relaying, we are prepared to consider some other fundamentals that apply to certain modern types.

Whenever tripping by a relay at one station has to be blocked by the operation of a relay at another station, the blocking relay should be more sensitive than the tripping relay. The reason for this is to be certain that any time the tripping relay can pick up for an external fault the blocking relay will be sure to pick up also, or else undesired tripping will occur.

The matter of contact "races" must also be considered. For example, refer to Fig. 3 where the "*b*" contact of the blocking relay must open before the overcurrent contact closes, when tripping must be blocked. With the scheme as shown, the overcurrent relay must be given sufficient time delay to make this a safe race. An ingenious scheme can be used to avoid the necessity for adding time delay, but this will be described later in connection with carrier-current-pilot relaying.

A further complication arises because of the necessity for using separate phase and ground relays in order to obtain sufflcient sensitivity under all short-circuit conditions. This makes it necessary to be sure that any tendency of a phase relay to operate improperly for a ground fault will not interfere with the proper operation of the equipment. To overcome this possibility, the principle of "ground preference" is employed where necessary. "Ground preference" means that operation of a ground relay takes blocking and tripping control away from the phase relays. This principle will be illustrated in connection with carrier-current-pilot relaying.

Some pilot-relaying equipments utilizing the blocking-and-tripping principle must have additional provision against improper tripping during severe power swings or loss of synchronism. Such provision will be described later.

A-C WIRE-PILOT RELAYING

A-c wire-pilot relaying is the most closely akin to current-differential relaying. However, in modern a-c wire-pilot relaying, the magnitude of the current that flows in the pilot circuit is limited, and only a two-wire pilot is required. These two features make a-c wire-pilot relaying economically feasible over greater distances than current-differential relaying.

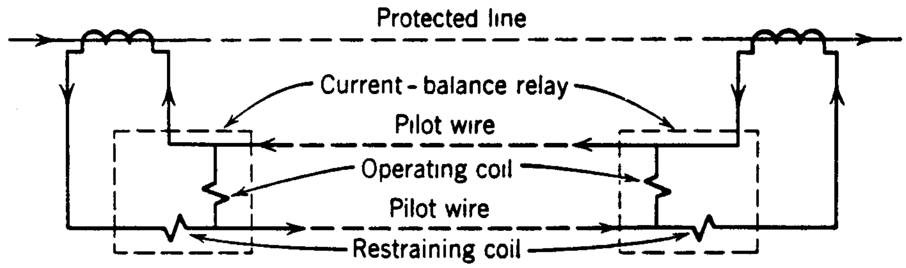

Fig. 4. Schematic illustration of the circulating-current principle of a-c wire-pilot relaying.

They also introduce certain limitations in application that will be discussed later.

First, we should become acquainted with two new terms to describe the principle of operation: "circulating current" and "opposed voltage." Briefly, "circulating current" means that current circulates normally through the terminal CT's and the pilot, and "opposed voltage" means that current does not normally circulate through the pilot.

An adaptation of the current-differential type of relaying described in Chapter 3, employing the circulating-current principle, is shown schematically in Fig. 4. Except that a current-balance relay is used at each end of the pilot, this is essentially the same as the percentage-differential type described in Chapter 3. The only reason for having a relay at each end is to avoid having to run a tripping circuit the full length of the pilot.

A schematic illustration of the opposed-voltage principle is shown in Fig. 5. A current-balance type of relay is employed at each end, and the CT's are connected in such a way that the voltages across the restraining coils at the two ends of the pilot are in opposition for current flowing through the line section as to a load or an external fault. Consequently, no current flows in the pilot except charging current, if we assume that there is no unbalance between the CT outputs. The restraining coils serve to prevent relay operation owing to such unbalance currents. But should a short circuit occur on the protected line section, current will circulate in the pilot and operate the relays at both ends. Current will also flow through the restraining coils, but, in a proper application, this current will not be sufficient to prevent relay operation; the impedance of the pilot circuit will be the

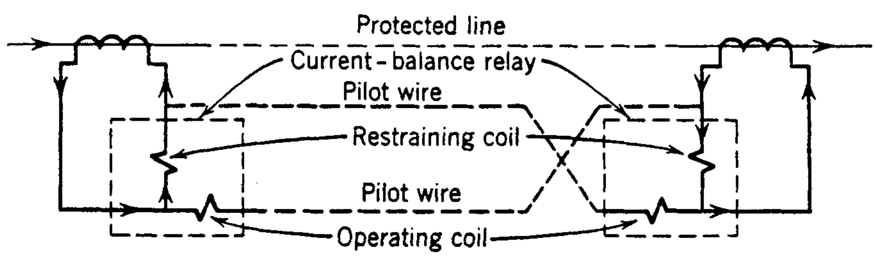

Fig. 5. Schematic illustration of the opposed-voltage principle of a-c wire-pilot relaying.

governing factor in this respect.

Short circuits or open circuits in the pilot wires have opposite effects on the two types of relaying equipment, as the accompanying table shows. Where it is indicated that tripping will be caused, tripping is contingent, of course, on the magnitude of the power-line current being high enough to pick up the relays.

	Effect of Shorts	Effect of Open Circuits
Opposed voltage	Cause tripping	Block tripping
Circulating current	Block tripping	Cause tripping

Both the opposed-voltage and the circulating-current principles permit tripping at both ends of a line for short-circuit current flow into one end only. However, the application of either principle may involve certain features that provide tripping only at the end having short-circuit-current flow, as will be seen when actual equipments are considered.

As has been said before, the feature that makes a-c wire-pilot relaying economically feasible, for the distances over which it is applied, is that only two pilot wires are used. In order to use only two wires, some means are required to derive a representative single-phase sample from the three phase and ground currents at the ends of a transmission line, so that these samples can be compared over the pilot. It would be a relatively simple matter to derive samples such that tripping would not occur for external faults for which the same currents that enter one end of a line go out the other end substantially unchanged. The real problem is to derive such samples that tripping will be assured for internal faults when the currents entering the line at the ends may be widely different. What must be avoided is a so-called "blind spot," as described in Reference 1 of the Bibliography. However, we are not yet ready to analyze such a possibility.

CIRCULATING-CURRENT TYPE

Figure 6 shows schematically a practical example of a circulating type of equipment.[2] The relay at each end of the pilot is a d-c permanent-magnet-polarized directional type. The coil marked "*O*" is an operating coil, and "*R*" is a restraining coil, the two coils acting in opposition on the armature of the polarized relay. These coils are energized from full-wave rectifiers. Here, a d-c directional relay is being used with rectified a-c quantities to get high sensitivity.

Although this relay is fundamentally a directional type, it is in effect a very sensitive current-balance relay. Phase-sequence filters convert the three phase and ground currents to a single-phase quantity. Saturating transformers limit the magnitude of the rms voltage impressed on the pilot circuit, and the neon lamps limit the peak voltages. Insulating transformers at the ends of the pilot insulate the terminal equipment from the pilot circuit for reasons that will be given later.

This equipment is capable of tripping the breakers at both ends of a line for an internal fault with current flowing at only one end. Whether tripping at both ends will actually occur will depend on the magnitude of the short-circuit current and on the impedance of

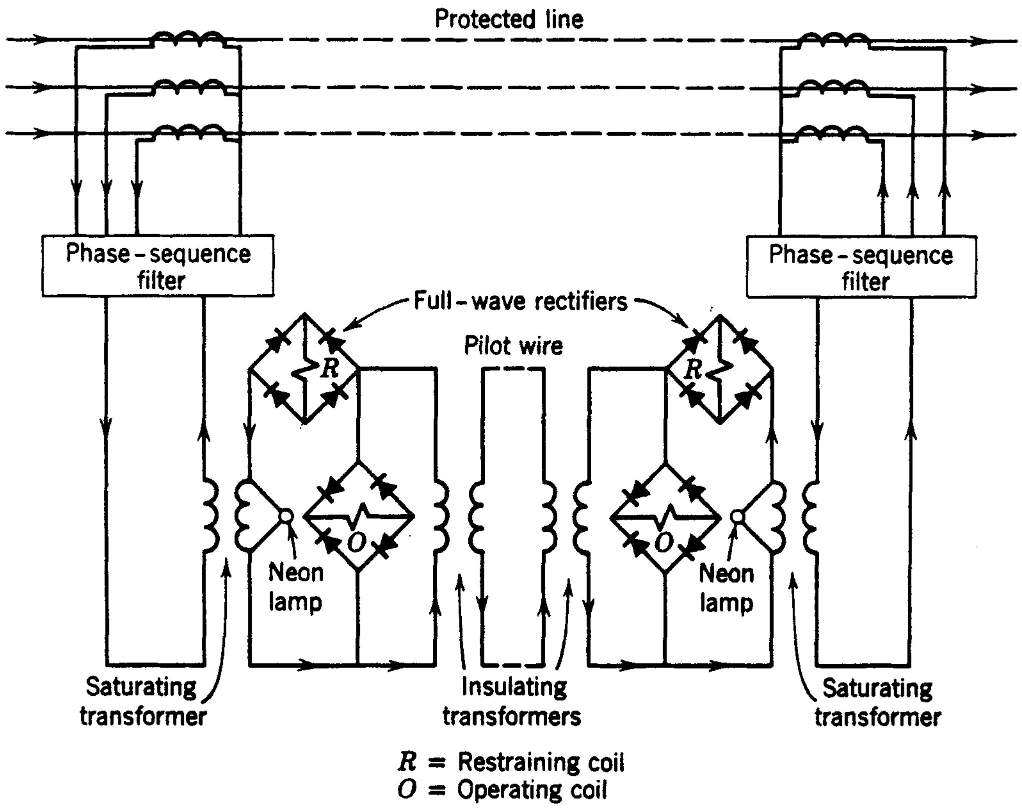

Fig. 6 Shematic connections of a circulating-current a-c wire-pilot relaying equipment.

the pilot circuit. This will be evident from an examination of Fig. 6 where, at the end where no short-circuit current flows, the- operating coil and the pilot are in series, and this series circuit is in parallel with the operating coil at the other end. In other words, at the end where fault current flows, the current from the phase-sequence filter divides between the two operating coils, the larger portion going through the local coil. If the pilot impedance is too high, insufficient current will flow through the coil at the other end to cause tripping there.

Charging current between the pilot wires will tend to make the equipment less sensitive to internal faults, acting somewhat like a short circuit between the pilot wires, but with impedance in the short circuit.

OPPOSED-VOLTAGE TYPE

An example of an opposed-voltage type of equipment is shown schematically in Fig. 7.[1] The relay at each end of the pilot is an a-c directional-type relay having in effect two directional elements with a common polarizing source, the two directional elements acting in opposition. Except for the effect of phase angle, this is equivalent to a very sensitive balance-type relay. The "mixing" transformer at each end provides a single-phase quantity for all types of faults. Saturation in the mixing transformer limits the rms magnitude of the voltage that is impressed on the pilot circuit. The impedance of the circuit connected across the mixing transformer is low enough to limit the magnitude of peak voltages to acceptable values.

The equipment illustrated in Fig. 7 requires enough restraint to overcome a tendency to trip for charging current between the pilot wires, although the angle of maximum torque of the operating directional element is such that it minimizes this tripping tendency.

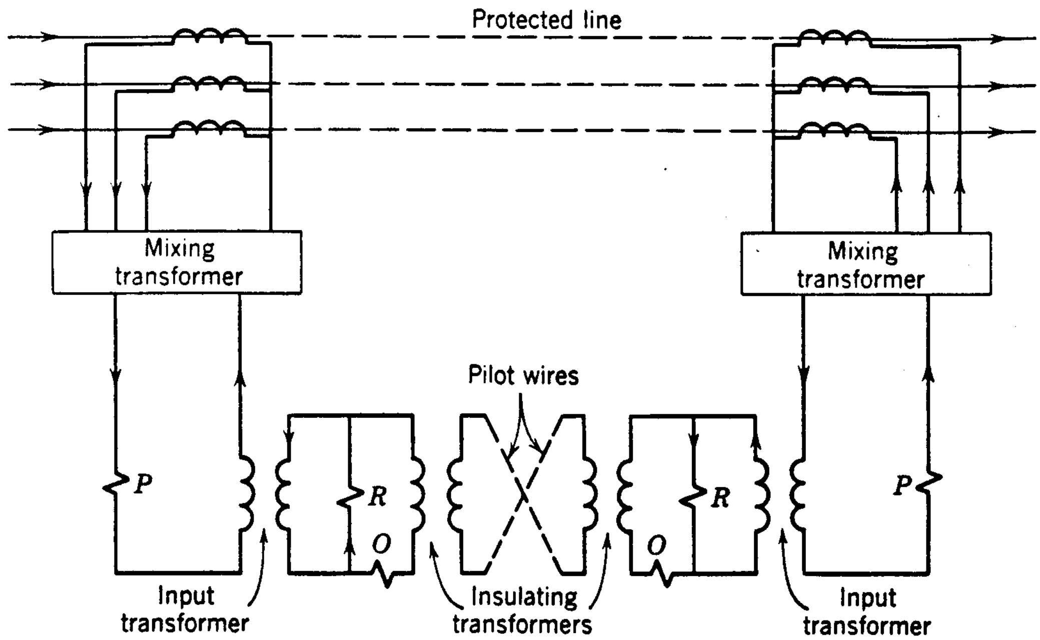

Fig. 7. Schematic connections of an opposed-voltage a-c wire-pilot relaying equipment. *P* = current polarizing coil; *R* = voltage restraining coil; *O* = current operating coil.

The equipment will not trip the breakers at both ends of a line for an internal fault if current flows into the line at only one end; it will trip only the end where there is fault current flowing. Current will circulate through the operating and restraining coils at the other end, but there will be insufficient current in the polarizing coil at that end to cause operation there. This characteristic is seldom objectionable, and it has the compensating advantage of preventing undesired tripping because of induced pilot currents.

ADVANTAGES OF A-C OVER D-C WIRE-PILOT EQUIPMENTS

Certain problems described in connection with d-c wire-pilot relaying are not associated with the a-c type. Since separate blocking and tripping relays are not used, the problem of different levels of blocking and tripping sensitivity are avoided. Also, the problems associated with contact racing and ground preference do not exist. Moreover, a-c wire-pilot relaying is inherently immune to power swings or loss of synchronism. In view of the simplifications permitted by the elimination of these problems, one can understand why a-c wire-pilot relaying has largely superseded the d-c type.

LIMITATIONS OF A-C WIRE-PILOT EQUIPMENTS

Both the circulating-current and the opposed-voltage types that have been described are not always applicable to tapped or multiterminal lines, because both types use saturating transformers to limit the magnitudes of the pilot-wire current and voltage. The non-linear relation between the magnitudes of the power-system current and the output of the saturating transformer prevents connecting more than two equipments in series in a pilot-wire circuit except under certain restricted conditions. Since this subject involves so many details of different possible system conditions and ranges of adjustment of specific relaying equipments, it is impractical to discuss it further here. In general, the manufacturer's advice should be obtained before attempting to apply such a-c wire-pilot-relaying equipments to tapped or multiterminal lines.

SUPERVISION OF PILOT-WIRE CIRCUITS

Manual equipment is available for periodically testing the pilot circuit, and automatic equipment is available for continuously supervising the pilot circuit. The manual equipment provides means for measuring the pilot-wire quantities and the contribution from the ends. The automatic equipment superimposes direct current on the pilot circuit; trouble in the pilot circuit causes either an increase or a decrease in the d-c supervising current, which is detected by sensitive auxiliary relays.[6] The automatic equipment can be arranged not only to sound an alarm when the pilot wires become open circuited or short circuited but also to open the trip circuit so as to avoid undesired tripping; in such cases, it may be necessary to delay tripping slightly.

REMOTE TRIPPING OVER THE PILOT WIRES

Should it be desired to trip the remote breaker under any circumstance, it can be done by superimposing direct current on the pilot circuit. If automatic supervising equipment is in use, the magnitude of the d-c voltage imposed momentarily on the circuit for remote tripping is higher than that of the continuous voltage used for supervising purposes.[7] Parts of the automatic supervising equipment may be used in common for both purposes. A disadvantage of this method of remote tripping is the possibility of undesired tripping if, during testing, one inadvertently applies a d-c test voltage to the pilot wires. To avoid this, "tones" have been used over a separate pilot.

PILOT-WIRE REQUIREMENTS

Because pilot-wire circuits are often rented from the local telephone company, and because the telephone company imposes certain restrictions on the current and voltage applied to their circuits, these restrictions effectively govern wire-pilot-relaying-equipment design. The a-c equipments that have been described are suitable for telephone circuits since they impose no more than the permissible current and voltage on the pilot, and the wave forms are acceptable to the telephone companies.[8]

The equipments that have been described operate without special adjustment over pilot wires having as much as approximately 2000 ohms d-c loop resistance and 1.5 microfarads distributed shunt capacitance. However, one should determine these limitations in any application.

PILOT WIRES AND THEIR PROTECTION AGAINST OVERVOLTAGES

The satisfactory operation of wire-pilot relaying equipment depends primarily on the reliability of the pilot-wire circuit.[3] Protective-relaying requirements are generally more exacting than the requirements of any other service using pilot circuits. The ideal pilot circuit is one that is owned by the user and is constructed so as not to be exposed to lightning, mutual induction with other pilot or power circuits, differences in station ground potential, or direct contact with any power conductor. However, satisfactory operation can generally be obtained where these ideals are not entirely realized, if proper countermeasures are used.

The conventional a-c wire-pilot relaying equipments that have been described tolerate only about 5 to 15 volts induced between the two wires in the pilot loop. For this reason, the pilot wires should be a twisted pair if the mutual induction is high. For moderate induction, wires in spiraled quads will often suffice if the other pair in the quad will not carry high currents. In addition to other useful information, Reference 4 of the Bibliography contains a method for calculating voltages caused by mutual induction

If supervising or remote-tripping equipment is not used, or, in other words, if there are no terminal-equipment connections to the pilot wires on the pilot-wire side of the insulating transformer, it is only a question of whether the insulating transformer and the pilot wires can withstand the voltage to ground that they will get from mutual induction and from differences in station ground potentials The insulating transformers can generally be expected to have sufficient insulation, and only the pilot wires need to be critically examined. But if supervising equipment is involved, or if the pilot wires may otherwise be grounded at one end and do not have sufficient insulation, additional means, including neutralizing transformers, may be required to protect personnel or equipment.[3, 4, 5, 8]

Pilot wires exposed to lightning overvoltages must be protected with lightning arresters. Similarly, pilot wires exposed to contact with a power circuit must be protected.

The subject of pilot-wire protection has too many ramifications to do justice to it here. The Bibliography gives references to much useful information on the subject. In general, the manufacturer of the relaying equipment should be consulted, and also the local telephone company, if a telephone circuit is to be used. The subject is complicated by the fact that it is necessary not only to protect the equipment or personnel from harm but also, in so doing, to do nothing that will interfere with the proper functioning of the relaying equipment. Such things as mutual induction, difference in station ground potentials, and lightning overvoltages generally occur when there is a fault on the protected line or in the immediate vicinity, at just the time when the proper operation of the relaying equipment is required.

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