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Indian Standard

APPLICATION GUIDE FOR ELECTRICAL RELAYS FOR ac SYSTEMS

PART V DISTANCE PROTECTION RELAYS

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BUREAU OF INDIAN STANDARDS
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

Gr 9 December 1969

Indian Standard

APPLICATION GUIDE FOR ELECTRICAL RELAYS FOR ac SYSTEMS

PART V DISTANCE PROTECTION RELAYS

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Indian Standard

APPLICATION GUIDE FOR ELECTRICAL RELAYS FOR ac SYSTEMS

PART V DISTANCE PROTECTION RELAYS

0. FOREWORD

0.1 This Indian Standard (Part V) was adopted by the Indian Standards Institution on 10 December 1968, after the draft finalized by the Relays Sectional Committee had been approved by the Electrotechnical Division Council.

0.2 Modern power systems are designed to provide uninterrupted electrical supply, yet the possibility of failure cannot be ruled out. The protective relays stand watch and in the event of failures, short circuits or abnormal operating conditions help de-energize the unhealthy section of the power system and restrain interference with the remainder of it and thus limit damage to equipment and ensure safety of personnel. They are also used to indicate the type and location of failure so as to assess the effectiveness of the protective schemes.

0.3 The features which the protective relays should possess are:

a) Reliability, that is, to ensure correct action even after long periods of inactivity and also to offer repeated operations under severe conditions;

b) Selectivity, that is, to ensure that only the unhealthy part of the system is disconnected;

c) Sensitivity, that is, detection of short-circuit or abnormal operating conditions;

d) Speed to prevent or minimize damage and risk of instability of rotating plant; and

e) Stability, that is, the ability to operate only under those conditions that call for its operation and to remain either passive or biased against operation under all other conditions.

0.4 A distance relay compares the local current with the local voltage as an economical substitute to an ideal protection scheme comparing local current with the remote current. As the operation of such a relay is made dependent on the ratio $U/I = Z$ (Z being the line impedance or a trigonometric function of it), it is also a measure of the line length. Hence the name 'distance' relay.

0.5 Besides being used for protection of feeders and transmission lines, the distance relays are sometimes also used for other applications, such as back-up for generators. However, this guide confines itself to only feeders and transmission lines.

0.6 This guide covers distance protection schemes comprising of electro-mechanical relays only. Distance protection schemes can be made of static and semi-static relays which have not been covered in this guide.

0.7 In the preparation of this guide considerable assistance has been derived from several published books and from manufacturers' trade literature. Assistance has also been rendered by State Electricity Boards in collecting actual examples.

0.8 It is emphasized that this guide has been prepared to assist in the application rather than to specify the relay to be used. This guide deals only with the principles of application of distance relays and does not deal with the selection of any particular protective scheme. The actual circuit conditions in all probability may be different from those given here. The examples, even though drawn from actual field applications, should be regarded as mere illustration of one or the other point.

0.9 This guide is one of the series of Indian Standard application guides for electrical relays for ac systems. The other guides in this series are:

IS : 3638-1966 Application guide for gas-operated relays

IS : 3842 (Part I)-1967 Application guide for electrical relays for ac systems : Part I Overcurrent relays for feeders and transformers

IS : 3842 (Part II)-1966 Application guide for electrical relays for ac systems : Part II Overcurrent relays for generators and motors

IS : 3842 (Part III)-1966 Application guide for electrical relays for ac systems : Part III Phase unbalance relays including negative phase sequence relays

IS : 3842 (Part IV)-1966 Application guide for electrical relays for ac systems : Part IV Thermal relays

1. SCOPE

1.1 This guide (Part V) deals with the application of distance relays for ac systems, covered by IS : 3231-1965*. It applies only to feeders and transmission lines.

NOTE — Distance protection schemes comprising of static and semi-static relays are not covered in this guide.

1.2 This guide does not cover the principles of system design and system protection.

2. TERMINOLOGY

2.1 For the purpose of this guide the definitions given in IS : 1885 (Part IX)-1966† and IS : 1885 (Part X)-1968‡ shall apply.

3. CLASSIFICATION ACCORDING TO POLAR CHARACTERISTICS

3.1 General — Distance relays are classified by their polar characteristics, number of inputs, and the manner in which the comparison is made. The common types compare two input quantities in either magnitude or phase to obtain characteristics which are either straight lines or circles when plotted on an $R - X$ diagram. The polar characteristics normally obtainable are:

a) Plain impedance;

b) Ohm:

   1) Blinder, and

   2) Reactance;

c) Mho;

d) Offset mho; and

e) Modified impedance.

3.1.1 Relay movements and circuits in which two independent quantities are compared are either inherently amplitude or phase comparators. Any type of characteristic obtainable with one comparator is also obtainable with the other, although the combinations of quantities compared in each case are different.

3.2 Plain Impedance Relay — The plain impedance characteristic shown in Fig. 1 is the simplest in use and consists of a circle with centre at the origin. Operation occurs in the shaded area inside the circle. The

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*Specification for electrical relays for power system protection.

†Electrotechnical vocabulary: Part IX Electrical relays.

‡Electrotechnical vocabulary: Part X Electrical power system protection.

significance of this is that the relay operates below a certain impedance level which is independent of the phase angle between voltage and current. The relay has a current-operating coil producing a torque equal to K_1I and a voltage-restraining coil producing a torque equal to K_2U. Relay operation occurs when $K_1I > K_2U$ or $\frac{U}{I}$ $(= Z) < \frac{K_1}{K_2}$.

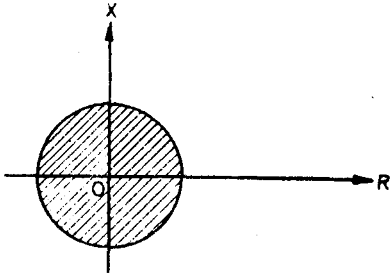


FIG. 1 CHARACTERISTIC OF IMPEDANCE RELAY

3.3 Ohm Relay

3.3.1 *Blinder Relay* — This relay has a straight line characteristic, parallel to the locus of the feeder impedance as shown in Fig. 2, and is used as a 'blinder' to prevent distance relays from tripping on very severe power swings and loads on long lines. The relay, which is sometimes referred to as an 'angle-impedance' relay can also be used for purposeful tripping of the tie lines at preselected locations, when the generators have gone out of synchronism. For this application, two such relays are required, which divide the impedance diagram into three zones, that is *A*, *B* and *C* (*see* Fig. 3). As no other condition except a power swing can cause the impedance vector to move successively through the three zones, the scheme is entirely immune to operation on any other type of system disturbance, for example, fault conditions.

3.3.1.1 Another application of the 'blinder' relay is in the protection of power lines for railway traction, where it is used to prevent operation of the distance measuring relays under maximum load conditions and shall ensure operation under minimum fault conditions.

3.3.2 *Reactance Relay* — This relay is a special case of the 'ohm' relay and has a polar characteristic which is a straight line parallel to the resistance axis as shown in Fig. 4. The concept of a relay measuring $\frac{U}{I}$ Sin $\phi = X$ was developed as such a relay would be independent of atmospheric effects, terrain or tower footing resistance and fault or arc resistance. While this is true for a radial line, it may not be equally applicable for meshed circuits.

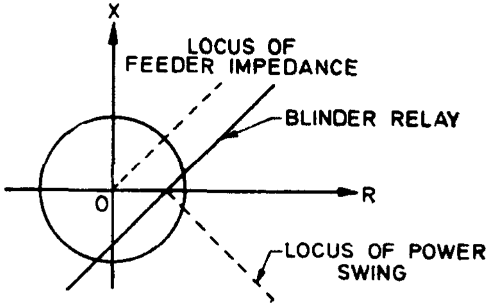


FIG. 2 CHARACTERISTIC OF OHM RELAY USED AS 'BLINDER'

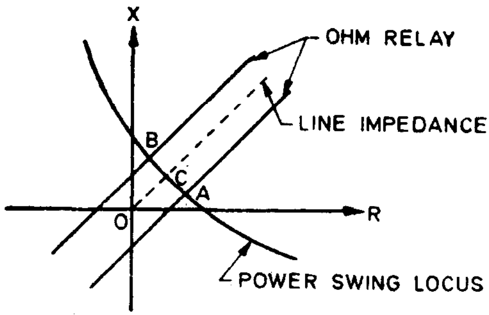


FIG. 3 CHARACTERISTIC OF OHM RELAY FOR OUT-OF-STEP TRIPPING

3.3.2.1 Reactance relays may have a reactive VA magnet instead of the voltage-restraining magnet of an impedance relay, and operate when

$$\frac{UI \text{ Sin } \phi}{I^2} \; (=X) < K$$

3.3.2.2 High speed aluminium cup type of relays with four poles are more sensitive than the above type and are used nowadays. Two opposite poles have current polarizing windings and the other two have one each of current-operating and voltage-restraining windings which oppose each other. The torque is thus made proportional to $KI^2 - UI \text{ Sin } \phi$ and the relay operates when $\frac{U \text{ Sin } \phi}{I} < K$ that is, $X < K$, the ohmic reactance setting of the relay

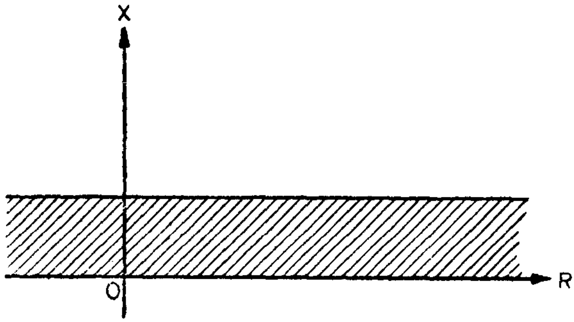


FIG. 4 CHARACTERISTIC OF REACTANCE RELAY

3.3.2.3 It, therefore, follows that the characteristic of a reactance relay is a straight line parallel to the R axis on the $R - X$ diagram and its reach in the third and fourth quadrant is infinite, that is, it is inherently non-directional. Therefore, in practice, a directional relay can be used either to keep the polarizing coils shorted or a separate directional relay is employed with the reactance relay.

3.4 Mho Relay — These relays have a circular characteristic with the circumference passing through the origin, as shown in Fig. 5. The term 'mho' was originally derived from the fact that the characteristic when plotted on an admittance instead of impedance diagram, gives a straight line. The mho relay is inherently directional and is suitable for use on long lines.

The majority of present day electromagnetic mho relays have a four pole cup type of movement, having voltage coils on two opposite poles and opposed current and voltage windings on the other two poles, giving a torque equation at balance as $U\,[\,KI \text{ Cos } (\theta - \phi) - U\,] = 0$ or $Z = K \text{ Cos } (\theta - \phi)$, where ϕ is the phase angle between U and I, while θ is the value of ϕ for maximum torque. This is the equation of a circle with diameter K.

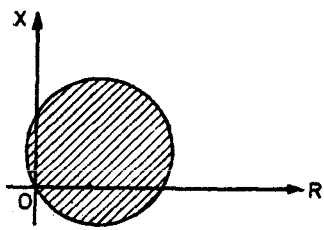


FIG. 5 CHARACTERISTIC OF MHO RELAY

3.5 Offset Mho Relay — The more general case where the circular characteristic of the plain impedance relay is offset by varying amounts is known as the ' offset-mho ' characteristic. Typical offset mho characteristic is shown in Fig. 6. The offset mho relay has four principal applications:

a) Bus-bar zone back-up protection,

b) Carrier starting in carrier-distance blocking schemes,

c) Out-of-step (or power swing) blocking, and

d) Starters on very long lines.

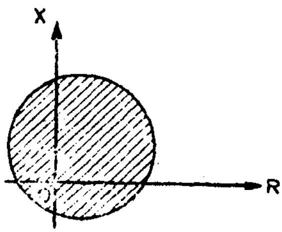


FIG. 6 CHARACTERISTIC OF OFFSET MHO RELAY

3.6 Modified Impedance — Modified impedance relay is a special case of the offset mho relay where the plain impedance relay is offset along the *R* or *R* and *X* axis to take care of arc compensation.

4. POLARIZING SUPPLIES

4.1 Of the three input quantities to impedance measuring relays, namely, operating current, restraint voltage, and polarizing input, the first two determine the complex impedance (*Z*) measured by the relay and are derived from the voltage and current associated with the fault. The third quantity is essentially a reference for determining the phase sense of the operating current and may be derived from a variety of quantities. The magnitude of the polarizing input is unimportant so long as it is not zero, for example, for terminal faults, when the restraint voltage is zero, the polarizing input should exist to avoid dead zone in the forward direction and to prevent maloperation for reverse faults.

4.2 The different methods in use for polarizing distance relays are given in **4.2.1** to **4.2.4**.

4.2.1 *Faulty Phase Voltage* — If the same voltage is used for polarizing as is used for the restraint voltage and the comparator input is derived through similar impedance, the polarizing signal disappears when the fault impedance is low and thus this method of polarization is not of practical use. It is worth noting, however, that the phase angle relation is always satisfied.

4.2.2 *Faulty Phase Voltage with Memory* — If, instead of applying the faulty phase voltage through an impedance similar to the restraint impedance to provide a polarizing input, an alternative impedance consisting of a tuned circuit is used, it is possible to maintain a polarizing signal for a short time after a fault occurs. Thus in the case of a terminal fault the polarizing input will be maintained sufficiently long for operation of the relay to occur. One of the drawbacks of this arrangement is that it is not effective when a line is being energized. The relay being initially de-energized, 'memory' is ineffctive under this condition. This disadvantage may be overcome by using busbar voltage transformers instead of line voltage transformers. However, when line voltage transformers are used, additional relays may be required in case of mho relays to ensure proper operation in case of solid three-phase faults.

The polarizing current does not maintain a constant phase relation to the faulty phase voltage. When a fault occurs, the phase angle of the faulty phase voltage alters whereas the memory circuit maintains a current at the original phase angle. This phase angle shift is not excessive and may be tolerated. A further and more serious cause of phase angle shifts is due to variations in the supply frequency. The resonant circuit always resonates at a fixed frequency whereas the supply frequency may vary between certain limits. To avoid trouble it is essential that 'memory' is restricted to about three cycles at the most. This implies that the relay shall be very fast.

4.2.3 *Healthy Phase Voltage* — A polarizing voltage may also be obtained from one of the healthy phases or between two phases. The main disadvantage of this method is that in the event of a three-phase terminal fault the polarizing voltage disappears. In a number of cases it has been possible to use high-set overcurrent relays which may protect against three-phase terminal fault.

4.2.4 *Faulty Phase Voltage with a Small Percentage from the Healthy Phases* — This condition is similar to that given in **4.2.1**, but has an additional 3 to 5 percent of the voltage from one of the leading phases in the voltage polarizing circuit. This voltage is phase shifted to bring it in phase with the faulted phase voltage. This increases the accuracy of distance measurement under low fault-voltage conditions. However, the method has similar limitations as those given in **4.2.3** under three-phase faults.

5. CLASSIFICATION ACCORDING TO TYPE OF COMPARATOR

5.0 As mentioned earlier, comparators are divided into two groups according to whether a comparison is made of the amplitude of the two input quantities or of the phase angle between them.

5.1 Amplitude comparators generally employ the following relay movements:

a) Balanced beam, and

b) Induction disc.

5.1.1 *Balanced Beam Relay* — Although quite outmoded, the balanced beam unit is used nowadays as an inexpensive starting element with limited range and accuracy requirements. In the relay, two magnitude circuits are arranged to act at the opposite ends of a beam, as shown in Fig. 7. Assuming that the turns are equal on the two coil systems and that the magnetic circuits are similar, operation is obtained when

$$|I_o|^2 \geqslant |I_r|^2 + K.$$

where

I_o = operating current,

I_r = restraining current, and

K = constant.

The advantages of this unit are simplicity and speed. The disadvantages are high-reset impedance, over-reach due to offset current waves or currents of high X/R ratio, elliptical impedance characteristics in undesirable direction, and a tendency to chatter. In modern practical relays, solutions to some of these problems have been found, for example, the dc offset component was extracted from the current wave by a filter to reduce the over-reach.

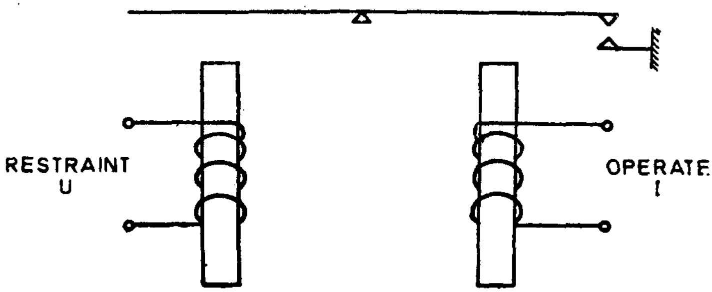


FIG. 7 BALANCED BEAM AMPLITUDE COMPARATOR

5.1.2 *Induction Disc (Amplitude Comparator) Relay* — By providing two entirely separate driving mechanisms on an induction disc as shown in Fig. 8, amplitude comparator is obtained. This unit suffers from most of the disadvantages of the beam relay and is much less efficient as it is slow in operation. As such it is not used in any modern distance protection scheme, and is of theoretical interest only.

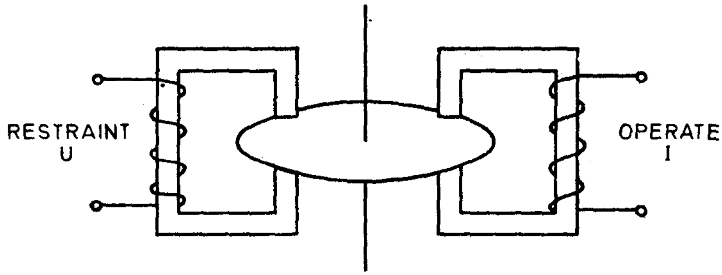


FIG. 8 INDUCTION DISC AMPLITUDE COMPARATOR

5.2 Phase angle comparators generally employ the following movements:

a) Induction disc, and

b) Induction cup.

5.2.1 *Induction Disc (Phase Angle Comparator) Relay* — A torque is obtained by the interaction of the fluxes from the two magnetic circuits which act in close proximity on the disc. The unit has a very low sensitivity and suffers from interaction between the two magnetic circuits. It is also difficult to balance and there is a tendency for spurious torques where only one input is applied. It is currently used in directional elements where high performance is not required.

5.2.2 *Induction Cup Relay* — The induction cup comparator is illustrated in Fig. 9. It is an improved version of the induction disc (phase angle) comparator and produces nearly perfect impedance characteristics, has almost equal operate and reset values and is not much affected by offset waves. The comparator may work over a larger range of input quantities and has very little interaction. The forces are proportional to the product of the input quantities. Its construction is compact and robust and it is the most popular high speed electromagnetic unit.

6. PERFORMANCE OF DISTANCE RELAYS

6.1 The ideal polar characteristics so far described are independent of the actual values of current and voltage applied to a distance measuring relay and depend only on the ratio of the input quantities. Practical distance relays depart from the ideal and have characteristics which depend on the actual values of voltage and current. An approximation to the ideal is obtained only over a limited range of input quantities.

Inside this range the relay will have errors which are acceptable and outside this range it will have excessive errors and may not operate. The operating time of the relay will be variable depending on the individual magnitudes of the input quantities, being, for example, long for small inputs near the cut-off impedance and short for large inputs well within the cut-off impedance. The reach accuracy of the relay also depends upon the proportionality between the respective torques and input quantities being maintained. However, depending upon the design of the relay, below a certain value of input voltage, this is no longer true and the relay may not be guaranteed to measure within the specified accuracy. The complete representation of a practical relay has thus to include information on these aspects in addition to the ideal polar characteristics.

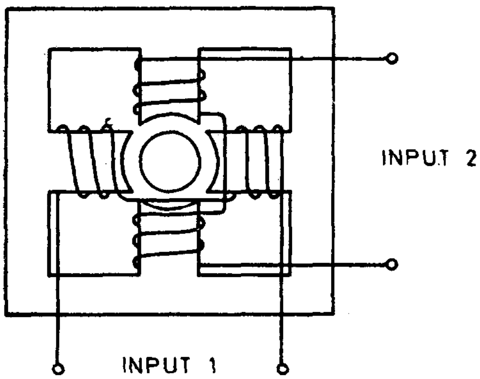


FIG. 9 INDUCTION CUP PHASE COMPARATOR

6.2 Any fault condition in a power system may be represented by a single line diagram as shown in Fig. 10. This simple impedance loop has a voltage U applied to it, which may be either the star or delta open circuit voltage of the power system, depending on the type of fault considered. R is identified as the relay location and I_R and U_R are the current and voltage applied to the relay respectively. The impedances Z_S and Z_L are the source and line impedances by virtue of their position with respect to the relay location. Source impedance Z_S is a measure of fault MVA at the relaying point and for faults involving earth, is also dependent on the method of system earthing behind the relaying point. Line impedance Z_L is a measure of the impedance of the protected section. The voltage U_R applied to the relay is thus $I_R Z_L$ for a fault at the reach point, and this may be alternatively expressed in terms of source to line impedance ratio, Z_S/Z_L, as follows:

$$U_R = I_R Z_L \qquad \text{.................................(1)}$$

where

$$I_R = \frac{U}{Z_S + Z_L} \qquad \text{.................................(2)}$$

Thus

$$U_R = \left(\frac{U}{Z_S + Z_L}\right)\left(Z_L\right)$$

$$= \frac{U}{\left(1 + \frac{Z_S}{Z_L}\right)} \qquad \text{.................................(3)}$$

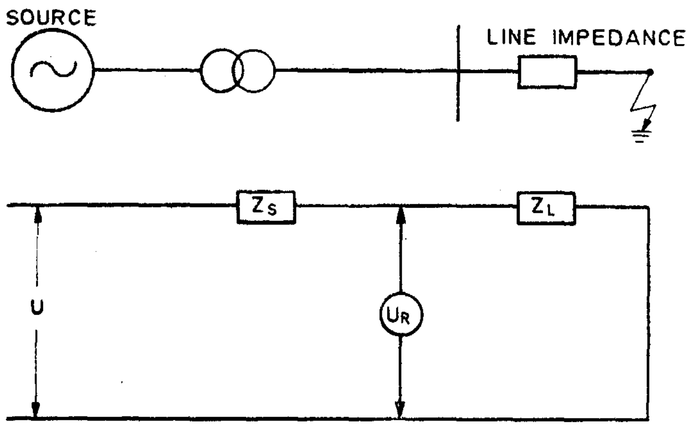


FIG. 10 PERFORMANCE OF A DISTANCE RELAY

6.3 It may be seen from equation 3 of **6.2** that the fault voltage 'seen' by the relay depends on the source-to-line impedance ratio of a transmission system. Relay performance is usually expressed in terms of the minimum 'fault voltage' that should be seen by the relay, for example, 8 V (secondary) across the relay terminals to maintain the accuracy of calibration within ± 10 percent. Therefore, the lower the value of the fault voltage across the relay to maintain the accuracy of calibration, the higher will be the Z_S/Z_L ratio that may be entertained, or in other words, the shorter the length of the line that may be protected. The 'minimum fault voltage' for a fault at the reach point to which the relay will remain accurate varies with the type of relay, that is, impedance, mho or reactance and also with the type of comparator employed.

6.4 Apart from the magnitudes of the impedances Z_S and Z_L, it is necessary to consider their phase angle. This determines the time constant of the primary transients which will occur in the voltage and current waveforms when a sudden fault is applied. With high speed relays this factor is of great importance as the relay is required to measure correctly during the transient period.

7. DISTANCE SCHEMES

7.1 Discriminating zones of protection may be obtained using distance relays provided that fault distance is a simple function of impedance. While in principle this is true for transmission circuits, the impedance actually measured depends on the actual magnitude of current and voltage, the relay connections, type of fault and impedances in the fault in addition to the line impedance. It is impossible to successfully eliminate these additional features in distance measurement for all possible operating conditions. However, a considerable measure of success is achieved using composite schemes employing several relays and different relay characteristics.

7.2 A distance scheme comprises starting relays, impedance measuring unit, zone timers and tripping relays. To cater for the economic and technical requirements of any particular network, a range of schemes is necessary from which a choice may be made. The schemes generally employed to meet the protection requirements of low, medium and high voltage networks, may be classified into three main groups:

a) Schemes designed for protection against phase faults only;

b) Schemes designed for protection against all types of faults — phase and earth — using separate units for each type of fault (also referred to as non-switched schemes); and

c) Schemes designed for protection against various type of faults using one set of units only but incorporating switching features (also referred to as switched schemes).

7.3 Typical schemes, falling under the three categories given in **7.2**, are given in Table 1.

8. STARTER RELAYS FOR DISTANCE PROTECTION

8.1 The primary function of the starter relays, sometimes also referred to as fault detectors, is to switch measuring relays to the correct input quantities of the measuring relays where the relays are not directionally connected (switched schemes) and to control the timing relays for extending the reach of the measuring relay to the second and third zone. Starter relays when used with distance relays of the impedance and reactance type, which do not possess any inherent directional property or additional direction measuring element, should incorporate directional feature in them.

8.2 The following types of 'starter' relays, for distance protection are used:

a) Overcurrent starters,
b) Undervoltage starters,
c) Impedance starters which may be of current dependent or current and angle dependent, and
d) Mho or offset mho starters.

TABLE 1 TYPICAL DISTANCE PROTECTION SCHEMES

(*Clause* 7.3)

SL No.	SCHEME	BASIC UNITS
1)	Three-zone phase fault protection (Non-switched)	a) i) Three mho units for phase fault measurement ii) Three mho units for starting b) i) Three reactance units for phase fault measurement ii) Three mho units for starting c) i) One mho unit for 3-phase fault measurement ii) One mho unit for phase-to-phase fault measurement iii) Three offset mho or elliptical starting units iv) One negative sequence starter
2)	Three-zone phase and earth fault protection (Non-switched)	a) i) Three mho units for phase fault measurement ii) Three mho units for earth fault measurement iii) Three mho units for starting b) i) Three reactance units for phase fault measurement ii) Three reactance units for earth fault measurement iii) Three mho units for starting c) i) Three mho units for phase fault measurement ii) Three reactance units for earth fault measurement iii) Three mho units for starting d) i) Three mho units for earth fault and 3-phase fault measurement ii) One mho unit for phase-to-phase fault measurement iii) Three offset mho or elliptical starting elements

(*Continued*)

TABLE 1 TYPICAL DISTANCE PROTECTION SCHEMES—*Contd*

SL No.	SCHEME	BASIC UNITS
3)	Three-zone phase and earth fault protection (switched)	a) i) One mho unit for fault measurement ii) Two instantaneous overcurrent starters NOTE — The mho unit is switched to the faulted phase by the overcurrent starters.
		b) i) One reactance unit for phase and earth fault measurement ii) One mho unit for directionalizing reactance unit iii) Three impedance starters NOTE — The mho and reactance units are switched to the faulted phase(s) by the starters.
		c) i) Three impedance units for phase and earth faults ii) Three directional units for phase and earth faults iii) Three impedance starters NOTE — The impedance and directional units are switched to measure either phase faults or earth faults by the starters.
		d) i) One mho unit for phase and earth faults ii) Three impedance starters iii) Overcurrent starters for earth faults NOTE — The mho unit is switched to the faulted phase by the starters.
		e) i) One mho unit for earth fault and 3-phase fault measurement ii) One mho unit for phase-to-phase fault measurement iii) Three offset mho or elliptical starter iv) One negative sequence starter
		f) i) Three impedance units for phase and earth faults measurement ii) Three directional units for phase and earth faults iii) Three impedance starters iv) Four overcurrent starters

8.3 Following combinations of distance and starter relays are commonly used:

a) Directional and overcurrent relays as starters for use with impedance type of distance relay;

b) Overcurrent units only for use with mho type of distance relay (sometime under-voltage relays are also used specially on resistance earthed systems);

c) Mho starters for any type of distance relay;

d) Impedance starters for reactance or impedance type of distance relay directionalized by a separate mho relay or a directional relay;

e) Current dependent under-impedance starters for distance relays when heavy loads on medium lines are expected. On heavy loads the reach of the starting relay reduces and at low currents the reach increases; and

f) Current and angle dependent under-impedance starters for distance relays where on heavy loads and long lines the reach, even at high current, is to be maintained in the fault area.

8.4 Choice of the type of starter deserves careful thought and depending upon the system conditions any of the starters mentioned above could be used. The mho type of starters should have a very wide range because they should be capable of detecting faults well beyond the zone-3 reach of the measuring relays. Where such a unit is used as a common starter for both phase and earth faults, residual compensation is necessary for the correct detection of earth faults.

8.5 For switched schemes, that is, employing one common measuring element to be switched to the appropriate phase(s) by the starter relays or their auxiliaries, the choice may be made between any one of the starters mentioned in **8.2**.

8.6 When overcurrent starters are used, care shall be taken to ensure that their setting is such that they would pick up for phase-to-phase and phase-to-earth faults, at the end of the zone-3 reach of distance relays, with minimum generation, yet they should not pick up for the heaviest overloads under maximum generation. These two conditions may not always be satisfied simultaneously. In such an instance, overcurrent starters should not be used. Furthermore, overcurrent starters should have a high pick up to drop out ratio, otherwise indiscriminate tripping may occur when there are tee-offs in the zone-2 and zone-3 sections, as this would prevent overcurrent starters from resetting after a zone-2 or zone-3 fault has been cleared by the relay of the faulty section.

8.6.1 Overcurrent starters have to be supplemented with 'under-voltage' type of starters to initiate the switching sequences on such earth faults which would prevent the overcurrent starters from picking up but would produce an undervoltage condition. This requirement calls for undervoltage starters to be set around 80 to 85 percent of the rated voltage. It should, therefore, be ensured that whenever undervoltage type of starters are employed, the system voltage under heavily loaded, but healthy conditions, is not so low as to affect the undervoltage starters.

8.7 An 'impedance' type of starter is, however, free from the drawbacks pointed out above for overcurrent and undervoltage types of starters. Care should be exercised to ensure that such starters have an ability to 'see' faults up to the end of zone-3 and to prevent incorrect switching. The starters on healthy phases should not pick up under an earthfault due to the extra 'sound phase' currents that would be flowing on multiple earthed systems. For this purpose, a knowledge of the system's 'sound phase' currents is necessary, along with the maximum load current.

9. IMPEDANCES SEEN BY DISTANCE RELAYS

9.1 To enable a distance relay to measure the same impedance, and hence the distance, under all types of fault conditions such as phase-to-phase, phase-to-earth and three-phase faults, appropriate voltages and currents should be available at the relay terminals. The actual impedance seen by a distance relay is:

$$= \frac{\text{Voltage available at the relay terminals}}{\text{Current flowing through the relay}}$$

$$= \frac{\text{Voltage transformer secondary voltage}}{\text{Current transformer secondary current}}$$

$$= \frac{\text{Voltage transformer primary voltage}}{\text{Voltage transformer ratio}} \times \frac{\text{Current transformer ratio}}{\text{Current transformer primary current}}$$

$$= \text{Primary impedance} \times \frac{\text{Current transformer ratio}}{\text{Voltage transformer ratio}}$$

$$= \text{Secondary impedance}$$

9.2 A distance relay required to measure correctly for phase-to-phase faults should be supplied with (a) phase-to-phase voltage and the difference of two phase currents as shown in Fig. 11A, or (b) be arranged in the three-phase single system scheme whereby the relay will measure all combinations of phase-to-phase faults.

9.2.1 The relay under the fault condition as shown in Fig. 11A would measure:

$$\frac{U_{RY}}{I_R - I^Y} = Z_1$$

that is, the positive phase sequence impedance of the single line conductor between the relay location and the fault position both under three-phase and phase-to-phase faults.

9.2.2 Similarly, for phase-to-earth faults as shown in Fig. 11B, if the relays were to measure positive phase sequence impedance Z_1, additional current, which is a function of the current transformer residual current (I_{Res}), should be fed into them. Therefore, the relay measures

$$\frac{U_{BN}}{I_B + KI_{Res}} = Z_1$$

Since $I_{Res} = 3I_0$ (I_0 = zero phase sequence current) for a phase-to-earth fault, it may be shown that the factor 'K' known as 'earth fault residual compensation' should be:

$$\frac{Z_0 - Z_1}{3Z_1}$$

where

Z_0 is the zero phase sequence impedance.

With the above amount of compensation, it may be shown that in a multiple earthed system where value of I_0 is unknown and may change with switching conditions, automatic adjustment of the amount of compensation may still be achieved by adding $\frac{1}{3}\left(\frac{Z_0 - Z_1}{Z_1}\right) I_{Res}$ to I_B, by using a compensating transformer connected in the residual circuits.

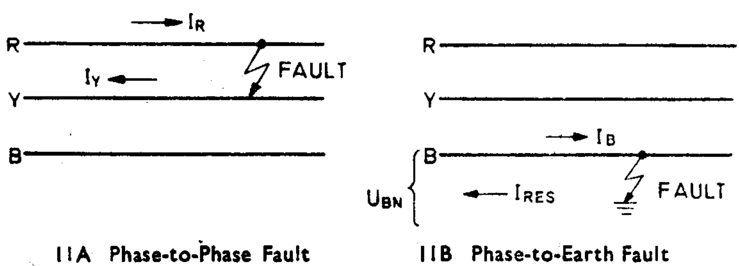


Fig. 11 Circuit Diagram for the Operation of Distance Relays Under Different Fault Conditions

10. APPLICATION OF DISTANCE RELAYS

10.1 Of the various applications possible for a distance measuring relay, its application to transmission line protection is the most common. Instead of the inverse time-distance characteristic used earlier, 'stepped' time-distance characteristics are now in use. The characteristics may either be 'single-stepped' or 'three-stepped' as shown in Fig. 12 and 13 respectively. A distance measuring relay of conventional design has an inherent instantaneous time-distance characteristic, the operating time becoming infinite at the relay reach point.

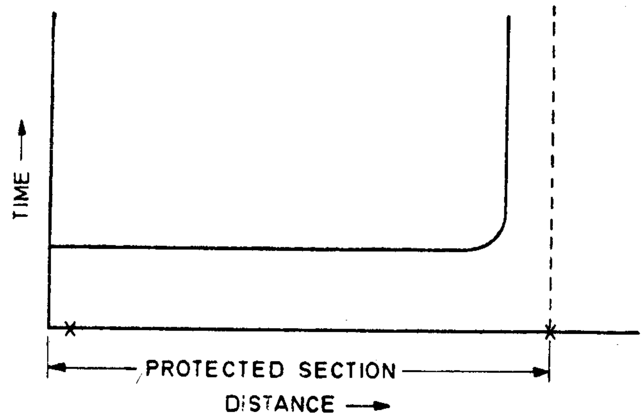


FIG. 12 TYPICAL SINGLE-STEP TIME-DISTANCE CHARACTERISTIC OF DISTANCE RELAYS

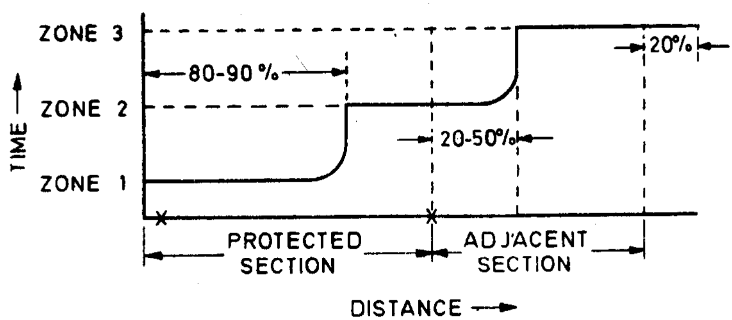


FIG. 13 TYPICAL THREE-STEP TIME-DISTANCE CHARACTERISTIC OF DISTANCE RELAYS

10.2 Owing to the limitations of time overcurrent protection on short feeders and on systems with wide variations in the generating capacity as given in IS : 3842 (Part I)-1967*, distance relays are used in preference, to overcurrent relays. Single-step distance relays can be used on feeders where high-set instantaneous overcurrent units cannot be used.

*Application guide for electrical relays for ac systems: Part I Overcurrent relays for feeders and transformers.

10.3 Another typical instance where 'single-step' distance protection may be employed is a transformer-feeder. In such a case, it would be possible to set the distance relay to cover 100 percent transformer-feeder length instantaneously because even on considering the 'over-reach' constituting factors such as 'offset wave' accuracy of the relay calibration, current transformer and voltage transformer errors and errors in line constants, it is often found that the relay will not 'look' through the transformer, or in other words, operate for transformer secondary side faults.

10.4 On transmission lines having an 'adjacent' line section as shown in Fig. 13, 'three-step' distance relays are used. The first step is usually set to cover up to 80 to 90 percent of the protected line section, and is instantaneous in operation. Setting the first step reach to about 80 to 90 percent of the protected section ensures that the relay will not over-reach and maloperate on faults close to the bus-bar of the adjacent section. This is necessary to allow for the inaccuracies, of the instrument transformers, errors in line constants, relay inaccuracies, and over-reach effect due to dc transients in the fault current. The setting of the first step should, therefore, take into account the above mentioned points.

10.4.1 The second step is set to extend between 20 to 50 percent of the next section. This ensures that the remote end faults of the protected section will be cleared in zone-2 time.

10.4.2 The third step is set to cover the entire adjacent section. It may, therefore, be surmised that the second and third steps of a three-step scheme serve as back-up to zone-1 protection of the adjacent section. Extention of the measuring relay reach into zone-2 and zone-3 is obtained by changing the taps of the auxiliary voltage transformers or by switching in resistance in the relay restraint circuit at pre-set time intervals by means of a timer relay, which is initiated by the starter relays on the inception of a fault. Alternatively, separate measuring relays may be used for zone-2 and zone-3. This latter arrangement, however, adds to the cost of the protection.

11. MISCELLANEOUS PROBLEMS ASSOCIATED WITH DISTANCE RELAYING

11.1 Under-Reaching of Distance Relays

11.1.1 Any phenomenon producing difference in the values of currents flowing past the relaying point and that flowing into the actual fault will result into an erroneous measurement leading to under-reaching, that is, the relay not being able to see a fault in its distance setting.

This may happen under the following circumstances:

a) When there is an infeed at the next bus-bar;
b) When there is fault impedance, usually present in the form of an arc; and
c) Earth faults on the secondary side of delta/star transformers being reflected as phase-to-phase fault on the primary side.

11.1.2 As shown in Fig. 14 the infeed I_F at the next bus-bar, which would be present if section *AB* itself was double circuit, would reduce the reach of relays at *A* as the additional current in section *BC* will not be seen by relays at *A*, although the additional voltage drop will be seen. Hence the impedance actually seen by the relay at *A* will be:

$$Z_F = \frac{(Z_{AB} \times I_A) + Z_{BD}(I_A + I_F)}{I_A} = Z_{AB} + Z_{BD}\left(\frac{I_A + I_F}{I_A}\right)$$

But as the relay can actually measure only $Z_{AB} + Z_{BD}$ for operation in zone-2, it would now be able to 'see' up to only Z_{BE}, in addition to Z_{AB}, such that

$$Z_{BE}\left(\frac{I_A + I_F}{I_A}\right) = Z_{BD} \qquad \text{.......................................(1)}$$

$$\text{or } Z_{BE} = Z_{BD}\left(\frac{I_A}{I_A + I_F}\right) \qquad \text{.......................................(2)}$$

From equation (2) above, it may be seen that however large may be the infeed I_F at the next bus-bar, the next bus-bar faults will always be covered in zone-2 of relays at *A*, which is their main function.

11.1.3 It has been said above that zone-3 shall cover the entire adjacent section. In Fig. 14, the worst case will be when section *BC* is single-circuit and section *AB* is double-circuit which would make $I_F = I_A$. Therefore, to cover entire section *BC* in zone-3, zone-3 should be set to

$$Z_{BC}\left(\frac{I_A + I_A}{I_A}\right) = 2 \times Z_{BC}$$

care should, of course, be exercised to see that $Z_{AB} + 2\ Z_{BC}$ is less than the load impedance.

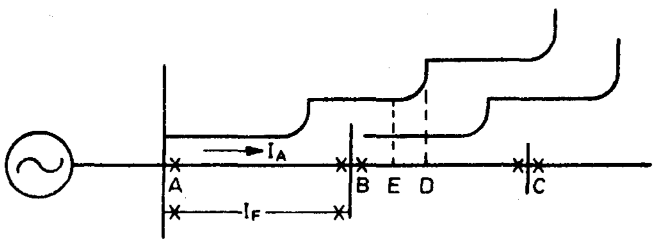


FIG. 14 UNDER-REACHING OF DISTANCE RELAYS DUE TO SEPARATE INFEED

11.1.4 *Under-Reach Due to Arcing*

11.1.4.1 Where mho or directional impedance relays are used for fault measurement, they also 'see' the fault-arc resistance which is quite appreciable at times and would cause under-reaching as shown in the vector diagram of Fig. 15. The under-reach due to arcing should thus be limited to such a value that all remote and bus-bar faults are cleared in zone-2 time. In other words, if the zone-2 setting is 50 percent of zone-1 setting, that is, extending 20 percent into the next section, the under-reach due to arcing should not exceed 20 percent (assuming both sections of equal length).

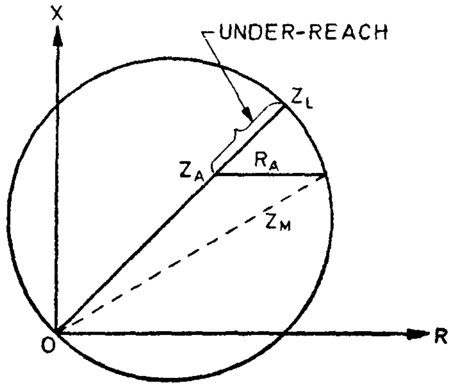


FIG. 15 VECTOR DIAGRAM FOR UNDER-REACH OF DISTANCE RELAYS

11.1.4.2 It has been emperically found that arc resistance

$$R_a = \frac{28\,650}{I^{1.4}} \text{ Ohms}$$

per metre length of the arc in still air. In general, if arc resistance exceeds one-third of the protected section impedance, the reach of a relay set to cover 85 percent of the section may shrink to 60 percent of the section. It follows, therefore, that only faults in the middle 20 percent, may be cleared instantaneously from both the ends. It should, however, be noted that for a phase-to-phase fault, the relay would 'see' $\frac{1}{2}R_a$. Further, as we are considering the effect of arc on zone-2, the time delay is sufficient to enable the arc to treble its initial value, given by the above formula, due to wind. Wind streches and deionises the arc and both these factors have a direct bearing on the arc resistance. Therefore, while calculating R_a by the formula

$$R_a = \frac{28\,650\, l}{I^{1.40}} \text{Ohms}$$

'l' being the length of the arc in metre ('l' should be greater than the conductor spacing of a line), mho relays tolerance to arcing may be increased by choosing the relay maximum torque angle to be less (lagging) than the line angle. Modified impedance relays can be set to take care of arc compensation without any under-reaching measurement as shown in Fig. 16.

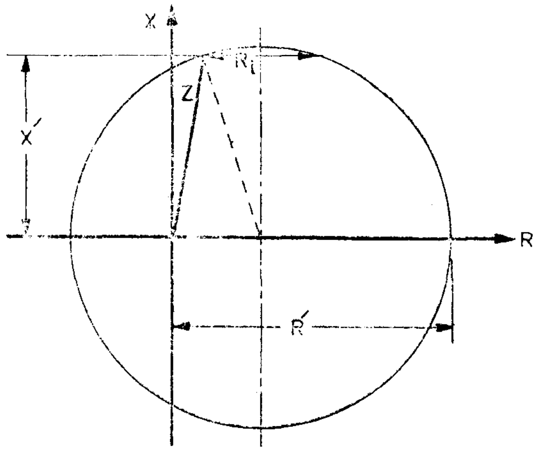


FIG. 16 MODIFIED IMPEDANCE RELAY CHARACTERISTICS WITH AND WITHOUT ARC COMPENSATION

11.1.4.3 Another method of increasing the tolerance of mho relays to arcing is to polarize them with voltage from another phase(s), that is, from unfaulted phases. This alters the reach of the mho relay under different fault conditions along the R axis. Thus the relay allows for more arc resistance.

11.2 Power Swings — Distance protection, not being a true unit protection, is affected by power swings on the system and may operate under these conditions. The locus of a power swing on the polar diagram is shown in Fig. 17. It will be noted that the locus of the power swing is at right angles to the general direction of the line impedances. In general, distance relays having mho characteristics are less susceptible to operation on power swings because of their narrower characteristics. If the system goes out of step, however, these relays will also operate. Because of this, special measures are taken to block operation during a power swing either by using an ohm-blinder relay as shown in Fig. 2 or by using an out-of-step blocking relay. The latter arrangement is shown in Fig. 18. The locus of the impedance vector 'seen' during a swing condition cuts the characteristics of both the blocking unit and the measuring unit. If the measuring unit operates within a certain time after the operation of the blocking relay, then tripping is allowed. If, on the other hand, after a predetermined time the measuring unit has not operated then an auxiliary relay opens a contact in the tripping circuit so that if the measuring relay does eventually operate tripping will not take place. Thus under fault conditions when the out-of-step blocking relay and the measuring relay operate practically simultaneously, tripping is allowed, but under power swing conditions when the measuring relay picks up after the out-of-step blocking relay, tripping is prevented. Thus the danger of cascade tripping of feeder sections is removed. Another application of out-of-step blocking relay is shown in Fig. 19. Two offset-mho relays are used to detect the presence of a power swing, and determination of whether the system is stable or unstable is made according to the time interval between the operation of these two relays.

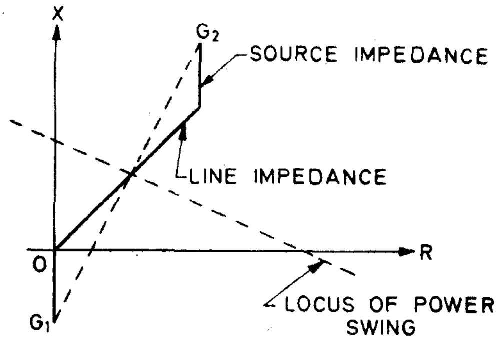
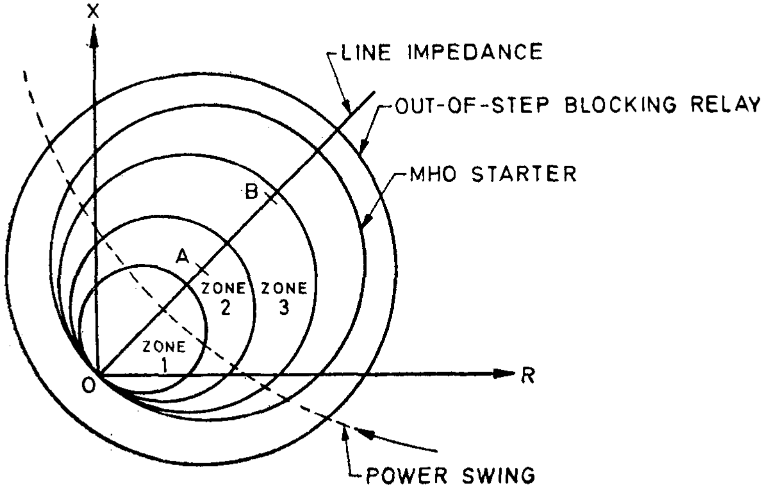


FIG. 17 LOCUS OF POWER SWING

.3 Double-Circuit Lines — Where two circuits are supported on the same towers or are otherwise in close proximity over the whole or part of their length, there is zero sequence mutual coupling between the circuits. Thus, during earthfault conditions, the voltage applied to a relay in one circuit includes an induced voltage proportional to the other. As the current distribution in the two circuits is unaffected by the presence of mutual coupling, no similar variation in the current applied to the relay takes place and consequently, the relay measures incorrectly. Whether the relay over-reaches or under-reaches will depend upon the direction of current flow in the healthy circuit. The amount of over-reach or under-reach is dependent on the line parameters, source and line impedances and the position of the fault. It should be noted, however, that the maximum amount of over-reach is restricted to the total length of the line and the cut-off point can never extend outside the line length. This is independent of the line parameters and compensation is, therefore, unnecessary in this respect. When the prospective under-reach from this and other causes is excessive, however, it may be prudent to employ carrier aided distance schemes or some other form of unit protection where high speed relay operation and simultaneous fault clearance by circuit breakers or both is considered necessary for all faults within the protected section. This would apply particularly where the parallel line section was followed by a short line. In this case faults near the end of the parallel line section may be cleared in zone-3 time if plain distance schemes are used.



OA = First line section
AB = Adjacent line section

Fig. 18 Characteristics of Out-of-Step Blocking Relay

11.4 Transients — The effect of transients on distance relays is to cause over-reaching or to introduce a delay in the relay operation. The former is due to the difference between the current and voltage transients applied to the relay, whilst the latter is generally the result of transient saturation of the protective transformers. The current and voltage transients at a relaying point due to a fault have the same time constants but their ratio of amplitudes depends on the source impedance which is widely variable. The system X/R ratio determines the duration of both transients while the instant of fault inception together with the system X/R ratio controls the initial amplitude of the current transient.

The amplitude of the voltage transient is inversely proportional to the source to line impedance ratio but also increases as the difference in the source and line angles increases. In a homogeneous system there is no transient voltage as the source and line angles are identical.

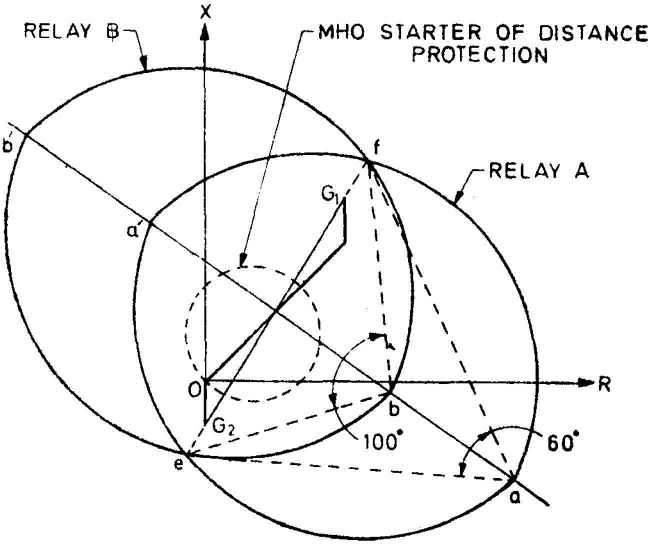


FIG. 19 OUT-OF-STEP BLOCKING SCHEME USING TWO OFFSET-MHO ELEMENTS (*A* AND *B*)

The effect of these transients is to increase the peak and rms values of current and voltage applied to the relay during the first few cycles of a fault. The current transient tends to increase the operating force and so causes over-reach, whilst the voltage transient increases the restraint force and causes under-reach. Since the voltage transient is always lower in magnitude, the net result is towards over-reach.

Where transient instability of a relay is merely due to mismatch between the transients in the current and voltage inputs, it may be corrected by either matching the transients by the use of secondary replica impedances or alternatively, by eliminating the transients altogether using filters; in the latter case at the cost of time delay.

Unfortunately, transients may cause saturation in current transformers due to the increased flux swing and this results in a possible delay in relay operation of several cycles. This condition is quite intolerable in situations where system instability may result from delay in fault clearance. Current transformer should be designed to withstand this flux swing without saturation when '1 cycle' distance relays are used.

11.5 Operating Time Characteristics — In practical relays, as the relationship between the operating current and restraint voltage directly affects the relay operating time, it varies with fault position and input current, being short for large inputs near the relaying point and long for small inputs near the reach point. Type of comparator used determines how sensitive a particular relay is and how far its operating time is affected by fault position and input current.

It is customary to present information on operating time by contour curves, similar to those shown in Fig. 20. From this figure, operating time may be determined for various fault positions and for various values of system source to line impedance ratios Z_S/Z_L. This method of representing operating time is now very common.

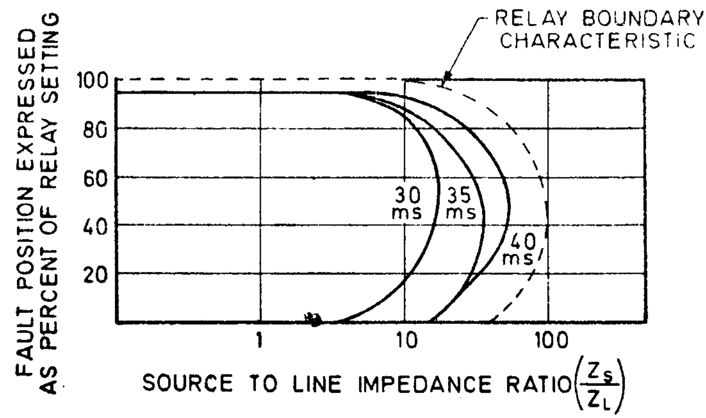
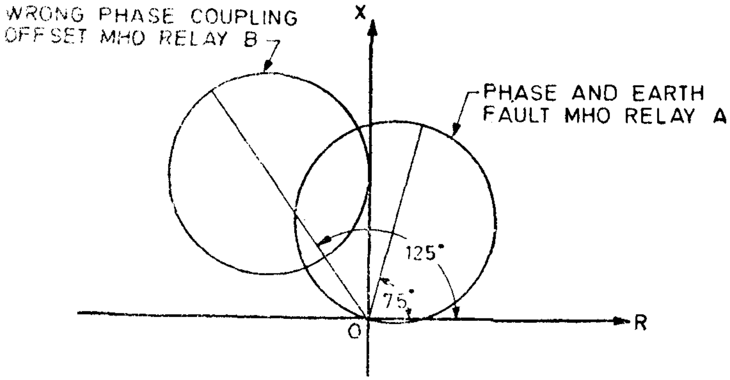


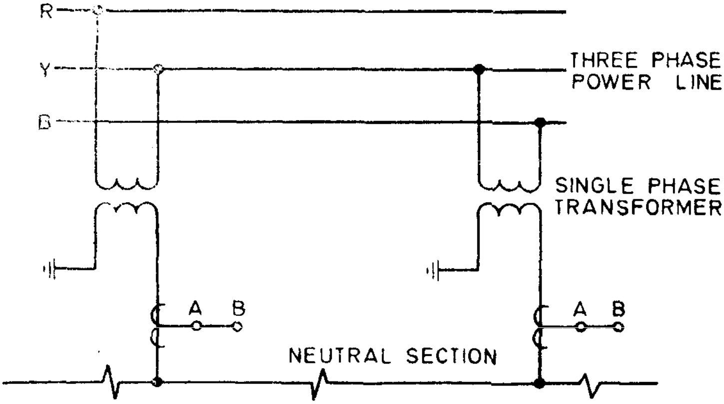
FIG. 20 TYPICAL OPERATING TIME CHARACTERISTICS

11.6 Application of Distance Relays to Electric Traction — Use of distance relays on single phase 25 kV railway overhead feeders has become common. A typical application is shown in Fig. 21. Two distance relays are normally used, one for phase-to-earth faults and second to guard against wrong phase coupling in case neutral section is accidentally 'bridged'. These relays have single instantaneous zone as no grading is involved.

Phase-to-earth fault relay is similar to the distance relays for three-phase lines. However, wrong phase coupling relay is normally provided with a maximum torque angle of 125° to 145°. It is preferable to provide a forward 'offset' for this relay to prevent it from operating on phase-to-earth faults.



21A Relay Characteristics

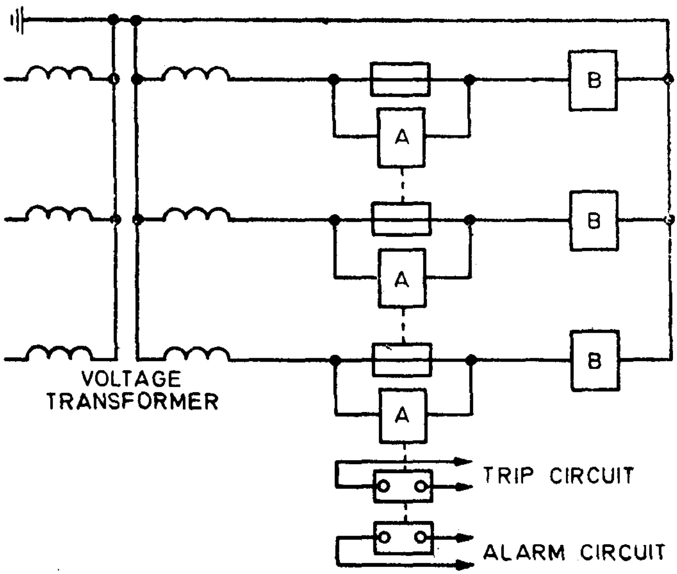


21B 25 kV Track Showing Relay Locations

FIG. 21 DISTANCE RELAYS FOR ELECTRIC TRACTION, 25 kV, SINGLE PHASE FEEDERS

12. EFFECT OF FUSE FAILURE

12.1 The basic principle of all distance measuring relays as shown above is the comparison of the restraining torque produced by the voltage and operating torque produced by the current. It follows, therefore, that with the current flowing in the operating direction, if the voltage at the relay were to vanish suddenly, as would be the condition on voltage transformer secondary fuse failure, the distance relay will operate. To prevent this form of virtual maloperation, fuse failure relays are used. A fuse failure relay is a simple device and is connected as shown in Fig. 22. On one or more main voltage transformer fuse blowing, the fuse failure relay will be energized. Fuse failure relays have normally closed contact which may be wired in series with the distance relay trip circuit to block the undesirable tripping impulse. The fuse failure relay should be provided with another pair of electrically separate contacts so that an alarm may be sounded.



A = Fuse failure relay
B = Distance relay voltage coils

FIG. 22 CONNECTIONS FOR FUSE FAILURE RELAY

12.2 It should, however, be ensured that the operating time of voltage transformer fuse failure relay is shorter than the distance relay zone-I operating time otherwise the fuse failure relays will get 'beaten' by the distance protection relays, which it is supposed to prevent from maloperation.

12.3 When fuse failure relay or miniature circuit-breakers are used, it should be ensured that the operating time of the same is shorter than the protection operating time and further more the starters do not maloperate under high resistance voltage transformer faults.

13. DISTANCE RELAYS IN CONJUNCTION WITH AUTO-RECLOSING AND CARRIER CHANNEL

13.1 Distance relays are often required to operate in conjunction with circuit-breaker auto-reclosing schemes to avoid unnecessary interruption of supply on transient faults which are by far the most predominant faults on overhead transmission systems. The requirements of successful auto-reclosing schemes are:

a) Simultaneous and 'instantaneous' de-energisation of the faulted line section from both the ends;

b) Allow a certain and minimum amount of 'dead' time to let the fault arc deionise; and

c) Close both ends of the line simultaneously.

13.1.1 For an auto-reclose to be successful, that is, the two systems pulling into step again after the momentary disruption it follows that the tripping and closing operations at the two ends should be 'simultaneous' and the time delay under **13.1**(b) should be as low as practicable.

13.1.2 The requirements of **13.1**(a) and **13.1**(c) are achieved by linking the protection at the two ends of a line by means of a 'carrier' channel. The carrier channel principle is used in the following forms;

a) Carrier-intertripping,

b) Carrier-blocking, and

c) Carrier-acceleration.

13.2 Carrier-Intertripping — Carrier-intertripping principle is shown in Fig. 23. The distance relays at the two ends *A* and *B* cover about 80 percent of the line length in their instantaneous zone-1. Therefore, faults occurring in the middle 60 percent of the line section are 'seen' by both the ends in zone-1 and their tripping is simultaneous. However, for faults occurring in the end 20 percent sections, the relay nearest the fault locates it in its zone-1 while the remoter relay locates the same in its zone-2. The nearer tripping relay is therefore made to send a carrier signal to the remoter nontripping relay to bring about simultaneous tripping of the whole line section. Once the two ends trip simultaneously, the auto-reclose relays take over.

13.3 Carrier-Blocking — One of the carrier-blocking principle is shown in Fig. 24. Here the carrier signal is utilized slightly differently. The distance relays at *A* and *B* are normally made to 'sit' in zone-2, that is, they are made able to 'see' upto 140 percent of the line length instantaneously. Therefore, for a fault anywhere along the line section, the relays at two ends trip simultaneously and the auto-reclosing sequences are initiated. However, for faults in the adjacent section, say at F_2, which may still be seen by relays at *A* in their instantaneous zones, relays at *A* are prevented from tripping by way of a carrier 'blocking' signal transmitted from the end *B*. The blocking signal is transmitted by reverse looking 'carrier-start' relays at *B* having their reverse reach somewhat greater than the zone-2 reach of the relays at *A* into the next section. On receipt of the carrier blocking signal, the relays at the receiving end step back to their usual zone-1 reach at 80 percent of the protected line section and thus allow relays at *C* to clear the fault in their zone-1. Relays at *A* offer back-up protection by their zone-2 and zone-3 reach and time-delay.

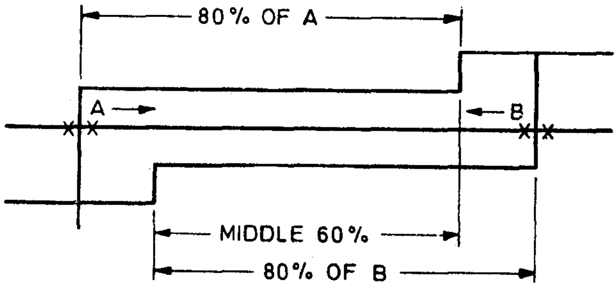


FIG. 23 CARRIER INTERTRIPPING

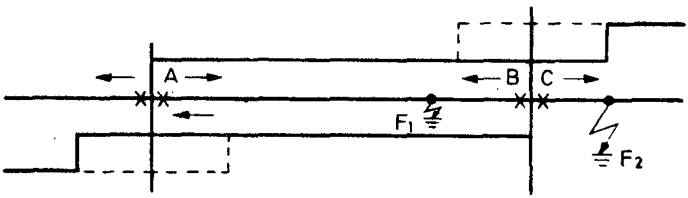


FIG. 24 CARRIER BLOCKING

13.3.1 It should be appreciated that the final tripping relays of a carrier blocking type of distance scheme should have a slight time delay on operation to wait for the carrier signal to be received from the other end in case the fault is external. If no carrier signal is received, the tripping is allowed to proceed. Otherwise, on receipt of a carrier signal the instantaneous zone-1 reach is promptly reduced as mentioned above. By using a fast carrier channel and carrier start relays, this time delay may be cut down. It is possible to achieve comparable times with modern blocking schemes with intertripping schemes.

13.4 Carrier-Acceleration — This principle is similar to carrier-intertripping except that the signal receiving end relays do not trip directly on receipt of a carrier intertrip signal. Instead, on receipt of the signal, the zone-1 reach of the relays is instantly extended to cover the entire protected section and tripping takes place after the relays at the signal receiving end have actually measured a fault. This principle introduces a slight time delay for remote end tripping as compared with the inter-tripping principle where tripping takes place as soon as the carrier is received.

13.5 From signalling point of view, the carrier-blocking principle is superior. The signal is transmitted over a healthy line and the only potential noise problem is during internal fault; at any other time, noise merely causes a harmless blocking signal. The intertrip and acceleration schemes on the other hand, always signal through a short circuited transmission line. Carrier-intertripping schemes are still sometimes favoured because they are cheaper than carrier-blocking schemes as the latter have to have additional reverse looking 'carrier start' relays apart from the usual set of measuring relays. However, for extra high voltage lines (220 kV and above) carrier-blocking schemes are generally preferred.

14. APPLICATION OF DISTANCE RELAYS TO TEED LINES

14.1 Application of distance relays to teed lines deserves careful thought and co-ordination. In the example given in Fig. 25, a fault at *F* may be seen by all the three relays, at *A*, *B* and *C*, in their zone-1. Ideally speaking, line *AB* should not trip. This is where 'carrier-blocking' principle is most usefully employed. The relays at *C* may have a carrier-blocking transmitter whereas relays at *A* and *B* may be the conventional carrier-blocking schemes with reverse looking 'carrier start' relays to take care of faults on the adjacent sections. With such an arrangement for faults down the line *CD* which fall within the instantaneous reach of all the three relays, station *C* will transmit a blocking signal to stations *A* and *B* and clear the fault first. Line *CD* may then have its own auto-reclosing scheme.

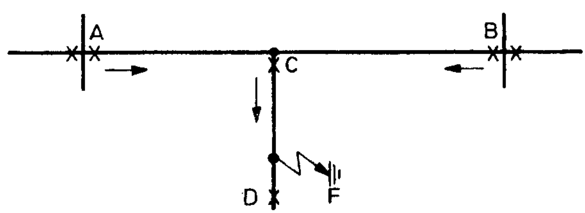


FIG. 25 APPLICATION OF DISTANCE RELAYS TO TEED LINES

14.2 Carrier-intertripping principle may also be employed here but it would necessitate foregoing of high speed auto-reclosing at *C*. For a fault at F, all the three stations will trip. A and B should auto-reclose as quickly as possible whereas C may either not reclose automatically at all, or have delayed auto-reclosing.

14.3 While choosing settings for such a multi-terminal line, it should be borne in mind that if the tee-off has a transformer right at the junction, then the 'instantaneous' reach of the relays at A and B should not normally extend beyond the transformers(s) at C. The lower the transformer impedance, for example, more units in parallel at a tee-off, the lower will be the instantaneous coverage possible for the main line relays at A and B.

14.4 It has been assumed in above discussion that there is no source connected at end D. Protection of each teed feeder requires special consideration and depends on various factors, for example, whether teed feeder is connected to a source, whether there is a transformer at 'tee-off', etc.

15. APPLICATION OF DISTANCE RELAYS FOR SINGLE-POLE AND THREE-POLE AUTO-RECLOSING

15.1 In applications where it is felt that single-pole auto-reclosing is desirable from system stability point of view, distance protection may be designed to meet this requirement. In case of 'switched' schemes the 'pole' selection is done by the starter relays auxiliaries, whereas in case of a non-switched scheme, it is provided by the respective phase measuring relays or their auxiliary trip relays. It is, however, ensured that for faults involving more than one phase, all the three phases are tripped as shown in Fig. 26. The function of contacts R_2, Y_2 and B_2 may also be performed by a '1 phase — 3 phase selector switch' which may be located either on the relay panel or at the circuit-breaker itself.

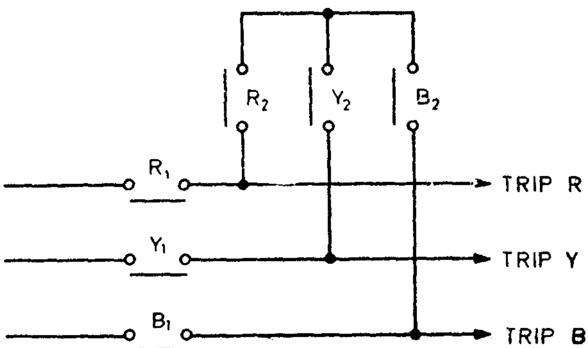


FIG. 26 APPLICATION OF DISTANCE RELAYS FOR SINGLE- AND THREE-PHASE AUTO-RECLOSING

16. INSTRUMENT TRANSFORMER CONNECTIONS

16.1 Impedances presented to the relay under different fault conditions depend upon the current transformer and voltage transformer connections and whether zero sequence compensation is used or not. These facts should be taken into consideration while setting the relays.

17. A TYPICAL EXAMPLE OF DISTANCE RELAY APPLICATION

17.0 General — Fig. 27 shows a typical 66/33/11 kV network. The calculation necessary for application of distance relays are carried out step by step. The requirements of the two lines, *A* and *B*, are identical.

As stated previously, it is useful for a manufacturer to declare the minimum voltage across the relay coils at which the relay will maintain the accuracy of its calibration within specified limits. In the system shown in Fig. 27, minimum voltage will occur when with minimum generation on the 66 kV side, given by the minimum fault level, only one 66/33 kV transformer is feeding the 33 kV bus-bar.

17.1 Step I — Check whether 80 percent of the proposed line length to be protected falls within the setting range available on the measuring relays:

80 percent of line impedance $= 0{\cdot}8 \times 5{\cdot}6 = 4{\cdot}48$ Ohms

Therefore, impedance seen by the relay, Z_S $= 4{\cdot}48 \times \dfrac{\text{Current transformer ratio}}{\text{Voltage transformer ratio}}$

$$\text{or } Z_S = 4{\cdot}48 \times \frac{400}{1} \times \frac{110}{33\,000} = 5{\cdot}98 \text{ Ohms}$$

This value should fall within the setting range of the relay.

17.2 Step II — Check the minimum voltage at the relay for a fault at zone-1 reach point for three-phase fault.

a) 66 kV source impedance on 33 kV bus-bar $= \dfrac{(33)^2}{500} = j2{\cdot}18$ Ohms

b) 66/33 kV transformer impedance at 33 kV bus-bar $= \dfrac{(33)^2}{30 \times \dfrac{100}{10}} = j3{\cdot}64$ Ohms

c) Line impedance for a fault at 80 percent point $= (2{\cdot}5 + j5{\cdot}0)\dfrac{(0{\cdot}8 \times 1{\cdot}2)}{(0{\cdot}8 + 1{\cdot}2)}$

$= (1{\cdot}2 + j2{\cdot}4)$ Ohms

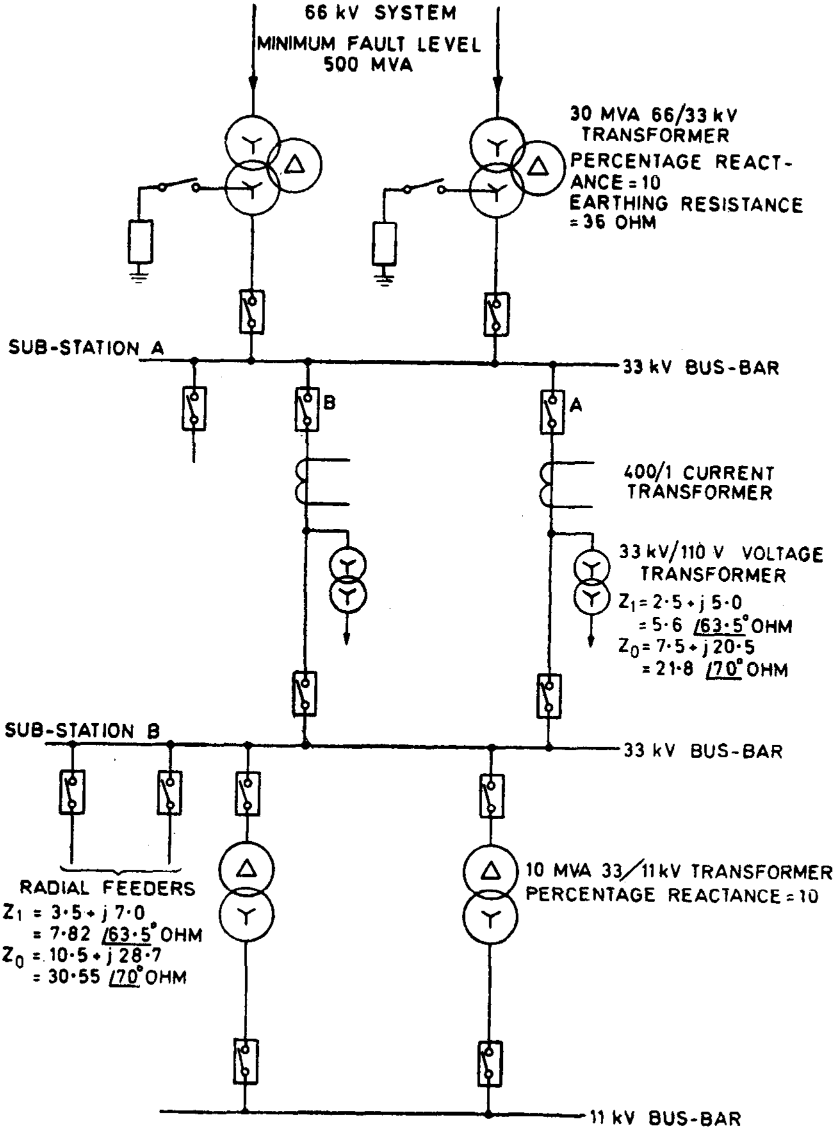


Fig. 27 Circuit Diagram of the Example on Application of Distance Relays

d) Total impedance up to the fault $= (j2{\cdot}18 + j3{\cdot}64 + 1{\cdot}2 + j2{\cdot}4)$
$= (1{\cdot}2 + j8{\cdot}22)$ Ohms

Therefore, total fault current $I_F = \dfrac{33\,000}{\sqrt{3}\,(1{\cdot}2 + j8{\cdot}22)} = 2\,290$ A

Therefore, voltage across the relay, U_r

$= \sqrt{3} \times I_F \times$ line impedance
$= \sqrt{3} \times 2\,290 \times (1{\cdot}2 + j2{\cdot}4)$
$= \sqrt{3} \times 6\,160$ volts (in terms of primary)

Converting this voltage in terms of secondary, we get

$$U_r = 6\,160 \times \frac{110}{33\,000} \times \sqrt{3} = 35{\cdot}5 \text{ volts (in terms of secondary)}$$

This voltage should be equal to or higher than the 'minimum voltage' figure quoted by the manufacturer.

17.3 Step III — Check minimum voltage at relay for phase-to-earth faults at zone-1 reach point:

We have $Z_e = \dfrac{(Z_1 + Z_2 + Z_0)}{3}$

For static equipment $Z_1 = Z_2$

Therefore, Z_e up to the fault point will be

$$= \frac{2\,(j2{\cdot}18 + j3{\cdot}64 + 1{\cdot}2 + j2{\cdot}4) + 3 \times 36 + \dfrac{(0{\cdot}8 \times 1{\cdot}2)}{(0{\cdot}8 + 1{\cdot}2)}\,(7{\cdot}5 + j20{\cdot}5)}{3}$$

$$= \frac{(110{\cdot}4 + j16{\cdot}44) + (3{\cdot}60 + j9{\cdot}85)}{3}$$

$$= \frac{114{\cdot}0 + j26{\cdot}29}{3}$$

$= (38 + j8{\cdot}76)$ Ohms

Therefore, $I_{FE} = \dfrac{33\,000}{\sqrt{3}\,(38 + j8{\cdot}76)} = 489$ A

Z_e of the lines for a fault at 80 percent

$$= \tfrac{1}{3} \left\{ \frac{0{\cdot}8 \times 1{\cdot}2}{0{\cdot}8 + 1{\cdot}2} \right\} \left\{ 2 \times (2{\cdot}5 + j5{\cdot}0) + (7{\cdot}5 + j20{\cdot}5) \right\}$$

$= \frac{1}{3}\,(2{\cdot}4 + j4{\cdot}8 + 3{\cdot}6 + j9{\cdot}85)$

$= \frac{1}{3}\,(6{\cdot}0 + j14{\cdot}65)$

$= (2{\cdot}0 + j4{\cdot}88)$ Ohms

$= 5{\cdot}3$ Ohms

Therefore $U_r = 489 \times 5{\cdot}3 \times \frac{110}{33\,000} = 8{\cdot}6$ volts (in terms of secondary)

This value U_r should be equal to or greater than the one specified by the manufacturer.

17.4 Step IV — Determination of Relay Settings — It should be noted that all relays are calibrated in positive sequence impedance.

17.4.1 To set zone-1 to cover 80 percent of the protected line:

Primary impedance $Z_1 = 2{\cdot}5 + j5{\cdot}0$

Primary impedance in terms of secondary (80 percent of the protected line) $= 0{\cdot}8 \times (2{\cdot}5 + j5{\cdot}0) \times \frac{400}{1} \times \frac{110}{33\,000}$

$= 2{\cdot}67 + j5{\cdot}34$

$= 5{\cdot}98 \,\underline{/63{\cdot}5^\circ}$ Ohms

Therefore, reactance relays should be set at 5·34 Ohms.

Since the line angle is 63·5°, mho relays with 60° maximum torque angle will be most suitable and they should be set at:

$$\frac{5{\cdot}98}{\mathrm{Cos}\,(63{\cdot}5 - 60^\circ)} = 6{\cdot}0 \text{ Ohms}$$

17.4.2 To set zone-2 to cover the protected line plus 50 percent of the next line section:

Primary impedance $Z_2 = (2{\cdot}5 + j5{\cdot}0) + \frac{1}{2}\,(3{\cdot}5 + j7{\cdot}0)$

$= 4{\cdot}25 + j8{\cdot}5$

Primary impedance in terms of secondary $= (4{\cdot}25 + j8{\cdot}5) \times \frac{400}{1} \times \frac{110}{33\,000}$

$= (5{\cdot}66 + j11{\cdot}33)$ Ohms

$= 12{\cdot}7 \,\underline{/63{\cdot}5^\circ}$ Ohms

Therefore, reactance relays zone-2 reach should be set to 11·33 Ohms.

The mho relays, with 60° maximum torque angle should be set to:

$$= \frac{12 \cdot 7}{\text{Cos}\ (63 \cdot 5 - 60)}$$
$$= 12 \cdot 8 \text{ Ohms}$$
$$= 13 \cdot 0 \text{ Ohms}$$

17.4.3 To set zone-3 to cover the protected line plus 125 percent of the next line section:

$$Z_3 \text{ (in terms of secondary)} = \left\{ (2 \cdot 5 + j5 \cdot 0) + 1 \cdot 25\ (3 \cdot 5 + j7 \cdot 0) \right\} \frac{400}{1} \times \frac{110}{33\,000}$$
$$= 9 \cdot 18 + j18 \cdot 35 \text{ Ohms}$$
$$= 20 \cdot 5 \underline{/63 \cdot 5^\circ} \text{ Ohms}$$

Therefore, reactance relays should be set at about, say, 20 Ohms. The mho relays should be set at:

$$\frac{20 \cdot 5}{\text{Cos}\ (63 \cdot 5 - 60)} = 21 \text{ Ohms.}$$

17.5 Step V — To check for positive operation of starters for faults at or just beyond zone-3 reach point:

$$Z_1 = j2 \cdot 18 + j3 \cdot 64 + \tfrac{1}{2}\ (2 \cdot 5 + j5 \cdot 0) + 1 \cdot 25\ (3 \cdot 5 + j7 \cdot 0)$$
$$= (5 \cdot 62 + j17 \cdot 07) \text{ Ohms}$$

$$\text{Therefore, line current} = \frac{\text{Line volts}}{\text{Loop impedance}} = \frac{33\,000}{2\,(5 \cdot 62 + j17 \cdot 07)}$$
$$= \frac{33\,000}{36 \cdot 0} = 915 \text{ A}$$

$$\text{Therefore, current in one line} = \frac{915}{2} = 458 \text{ A}$$
$$= \frac{458}{400} \text{ A (in terms of secondary)}$$
$$= 1 \cdot 14 \text{ A (in terms of secondary)}$$

Should this setting be considered too low in relation to the feed at substation 'B', then 'mho' or impedance type starters should be used, with the same setting or just greater than zone-3 setting that is, 21 Ohms.

17.6 Step VI — Zone-2 and Zone-3 Discrimination — If the zone-2 or zone-3 reaches of the distance relays look beyond the 33/11 kV transformers, then the time delay of zone-2 and zone-3 should grade with the 11 kV protection. In this instance:

$$\text{Parallel impedance of transformers} = \frac{10}{100} \times \frac{(33)^2}{20}$$
$$= j5 \cdot 45 \text{ Ohms.}$$

Therefore, impedance from the relaying point $= (2.5 + j5.0) + j5.45$

$= (2.5 + j10.45)$ Ohms (primary)

In terms of secondary, this impedance is:

$$= (2.5 + j10.45) \frac{400}{1} \times \frac{110}{33\,000}$$

$$= (3.33 + j13.9) \text{ Ohms}$$

Reactance relays zone-2 reach is worked out to be 11.53 Ohms.

Therefore, zone-2 will not look into 11 kV faults. Zone-3 reactance relays reach is worked out to be 20 Ohms. As the fault reactance is only 13.9 Ohms, zone-3 relays will see 11 kV side faults; hence zone-3 time should be graded with the 11 kV protection. Mho relays will be similarly affected.

17.7 Step VII — To Check Under-Reach of Zone-2 and Zone-3 — Because zone-2 and zone-3 fault currents will be shared by the two parallel lines equally, for zone-2 faults, the relays will actually see:

$$(2.5 + j5.0) + 0.5\,(3.5 + j7.0) \times \tfrac{1}{2}$$

$= (3.375 + j6.75)$ Ohms (in terms of primary)

$= (4.0 + j9.0)$ Ohms (in terms of secondary)

But Zone-2 reactance relays are actually set at 11.33 Ohms

Therefore, percentage under-reach $= \dfrac{11.33 - 9.0}{11.33} = 20.6$ percent

Similarly, the measured impedance for zone-3 will be

$$(2.5 + j5.0) + 1.25\,(3.5 + j7.0) \times \tfrac{1}{2}$$

$= (4.69 + j9.38)$ Ohms (in terms of primary)

$= (6.25 + j12.5)$ Ohms (in terms of secondary)

But zone-3 reactance relays are actually set at 20 Ohms.

Therefore, under-reach for zone-3 $= \dfrac{20 - 12.5}{20} = 37.5$ percent.

Therefore, as already pointed out earlier, if load impedance permits, zone-3 reach should be set to cover 125 percent of the adjacent line section taking into consideration the division of fault current along the parallel lines. That is, the zone-3 should be set at:

$$(2.5 + j5.0) + 2 \times 1.25\,(3.5 + j7.0)$$

$= 15.0 + j30.0$ Ohms (in terms of secondary)

A similar check can be carried out for mho relays.

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