2. Ensuring that when the same power is being carried by the two transformer windings, the same flows to the relay from both sides and that, at the full power of the winding, the current flowing to the relay is at least 0.7 times the relay current.

3. Filtration of zero-sequence currents when the transformer neutral is earthed, or in auto-transformers. For this purpose the auxiliary C.T. shall be connected in star/delta on that side of the transformer which has its neutral earthed.

4. Auxiliary C.T. should never be employed on only one side. With an asymmetrical arrangement the different transient response of the two circuits in the event of through short circuits can give rise to considerable difference currents which could cause the extremely rapid relay to operate.

In order to keep the burden on the auxiliary C.T. as small as possible, they should be mounted as close to the relay as can be permitted.

Apart from individually matched auxiliary c.t., it is also possible to supply universal c.t. which are suitable for use in the majority of cases.

Summary

Static differential relays are preferred for protection of large generators and transformers. The principle is similar to that of conventional differential protection. Additional auxiliary transformers are used in secondary circuit of main CT's. The output of operating auxiliary CT and restraining auxiliary CT is supplied to rectifier bridge comparator. A permanent magnet moving coil relay is used as tripping device.

QUESTIONS

1. Describe the circuit of static differential relay for protection of two winding transformer.
2. Describe the circuit of a static differential relay for three winding transformer.
3. Write short notes on any two :
   — use of rectifier comparator in static differential protection of two winding transformers
   — advantages of static differential protection
   — inrush proofing in static differential protection of power transformers.
4. Describe the difficulties in conventional differential protection of power transformers. State the merits of static protection. Explain clearly the additional features in static protection schemes.
5. Describe the rectifier bridge comparator used in static differential protection of power transformer. Illustrate the provision of blocking during inrush currents.
6. Explain the requirements of main and auxiliary CT's (intermediate CT's) in static differential relays.

42

Static Distance Relays and Distance Protection of EHV Lines

42.1. INTRODUCTION

The principles of distance protection are discussed in Ch. 29 and distance protection of transmission lines is described in section 30-*B*. The principles of carrier aided distance protection have been briefly mentioned in sec. 30.14.

This chapter deals with *advanced topics in distance protection of HV and EHV lines with particular reference* to static distance relays.

The principle of measurement of impedance (distance) is the same in both electromagnetic relays and static relays (Ref. Sec. 29). However static distance relays offer several advantages.

Merits of Static Distance Relays.

— no moving parts in measuring circuit, hence no effect of vibrations, shocks, dust.
— faster operation 20 ms, 40 ms, 60 ms
— less burden *e.g.*, burden of CT : 0.9 VA to 4.2 VA during normal and short circuit conditions respectively. Burden on VT : 2.2 to 12 VA during normal and short-curcuit condition respectively. This results in more economical CT's, VT's and better accuracy.
— comparator with elliptical or quadrangular impedance characteristics on R -X plane can be used. Such characteristics are *not* possible by electromagnetic distance relays whose characteristics are limited to sectors of circles on R-X plane.
— greater adoptability due to large range of adjustments and characteristics.
— Versatile range of relays available for various specific applications.
— better stability under power swing conditions.
— suitable for long heavily loaded lines, cables, even distribution lines.
— cover all types of faults selectively, *e.g.*, single line to ground, line to line, three phase.
— can have distance time step characteristic with four *independently* adjustable time steps and impedance zones.
— lower impedance setting possible
— fast tripping of first step — selector switches for
  — under reach and over-reach
  — rapid auto-reclosure or delayed reclosure
  — programmed auto-reclosure
— provision of contacts for remote annunciation of kind of fault, step of operation, tripping
— possibility of temporary reversal of measurement direction of second or second and thrid zones.

— compact size ($450 \times 750 \times 200$ mm) of a three phase, four step relay and less weight (50 kg) compared with several electromagnetic relays accommodated on a complete separate panel to perform similar functions.

— No wonder, static distance relays with their several merits are rapidly replacing their electromagnetic competitors. There are two distinct applications of these relays.

— medium high voltage (12 kV, 36 kV, 72.5 kV) distribution lines where multistage distance relays are now replacing usual overcurrent time delay relays. By distance schemes it is possible to have greater selectivity, shorter interruption times.

— EHV transmission line (145kV, 245kV, 420 kV) in conjunction with carrier signals. The main advantage of carrier aided distance protection schemes is that only tripping or blocking command is transmitted over transmission line. Transmission of pure command (not derived from main current) in digital values, provides greater security in transmission to the condition.

Section 1. COMPARATOR COMBINATIONS IN DISTANCE RELAYS

42.2. VOLTAGE COMPARATOR AND CURRENT COMPARATOR

As described earlier, the distance relay compares the ratio $\frac{V}{I}$. It is set to an impedance $\frac{V}{I} = Z$, such that for a fault at a certain distance from relay location the relay operates if the impedance of the line, upto the fault point is less than the above relay setting Z.

The versatile family of distance relays includes impedance relay, Reactance relay, Mho relay discussed earlier. The measurement of impedance, reactance or admittance is done by comparison of input combinations of current and voltage. Hence distance relays have input current and voltage. In static comparators the two quantities to be compared must be similar, *e.g.* current/current or voltage/voltage.

Voltage Comparator

Current I is converted into equivalent voltage V_A by producing a voltage drop in an impedance Z. The voltage drop is then compared with other voltage (Fig. 42.1).

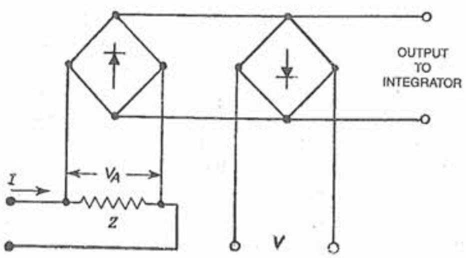


Fig. 42.1. Distance relay based on voltage comparison principle.

Block Diagram of a Static Distance Relay

A block diagram of a static distance relay is given in Fig. 42.2. The line *PT* secondary is connected to auxiliary *PT*. The output of VT is converted into current. This is compared with the output of VT.

Let us come back to Fig. 42.1. In voltage comparator, the current is converted into voltage by passing it through impedance $Z < \theta$ which is a replica of the protected line section on a secondary basis. It means the IZ drop given to the rectifier bridge is compared with to line voltage V.

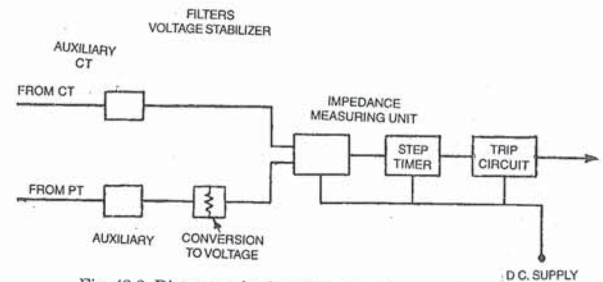


Fig. 42.2. Distance relay based on current comparison principle.
[*Courtesy* : Brown Boveri, Switzerland.]

Current Comparator

Alternatively in current comparator, a current is derived from CT and the voltage from VT is converted into equivalent current V/Z by connecting a replica impedance (impedance which is a small scale version of line impedance) in series in VT secondary (Fig. 42.3).

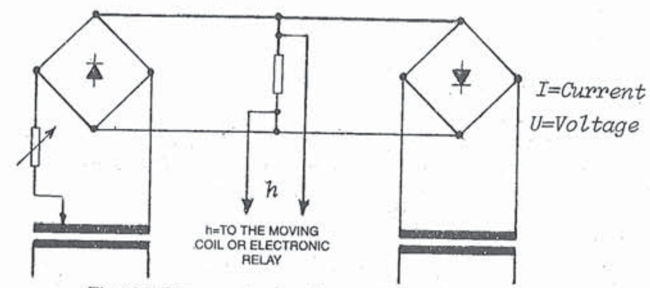


Fig. 42.3. Distance relay based on current comparison principle.
[*Courtesy* : Brown Boveri, Switzerland.]

The current is secondary of VT corresponds to V/Z which is compared with I.

The use of replica (image) impedance permits faster tripping as it eliminates errors due to transients in fault current. This needs explanation. The transient d.c. component of current passing through line impedance produces a faithful voltage waveform which is derived from line VT. The secondary current of line VT (V/Z) has faithful transient. The comparator compares V/Z and I, both having identical transient (assuming faithful reproduction). Hence the effect of transient is cancelled out from Impedance Measurement.

The use of replica impedance reduces the influence of harmonic and transient d.c. components substantially.

The rectifier bridge current comparator (Fig. 42.4) receives two current inputs, say operating input I_O and restraining input I_R. The output of comparator is applied to a permanent magnet coil relay or a static level detector.

In distance relays, I_O *and* I_R *may be supplied either by the current transformer by a voltage transformer through a series impedance (Fig. 42.3) or by both sources in a particular combination to obtain particular relay characteristic.*

(*i*) **Impedance Relay**

If restraining current I_R is supplied by voltage transformer, and operating current I_O is supplied by current transformer (Ref. Fig. 42.4), the relay operates when the ratio V/I is less than a certain value Z_N and is therefore a minimum Impedance Relay.

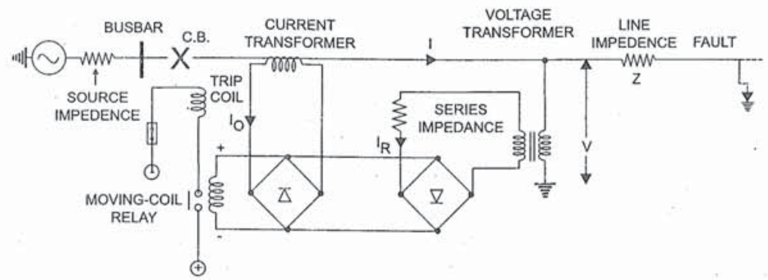


Fig. 42.4. Comparator used in an impedance relay. [*Courtesy* : A Reyrolle and Co. Ltd., England.]

(*ii*) **Directional Impedance Relay**

If I_R is supplied by current transformer and also by voltage transformer ($I_R = K_1I - K_2V$) and I_O is supplied by current transformer and voltage transformer ($I_O = K_1I - K_2V$), the relay operates when

$$I_0 > I_R$$

i.e. $$K_1I + K_2V > K_1I - K_2V$$

With this characteristic, the relay operates for a particular phase relation between V and I, restrains for some other.

In other words the relay has *Directional Characteristic.*

Here directional characteristic has been obtained by a particular combination of inputs to the comparator. (Ref. Fig. 42.5) through auxiliary mixing transformer.

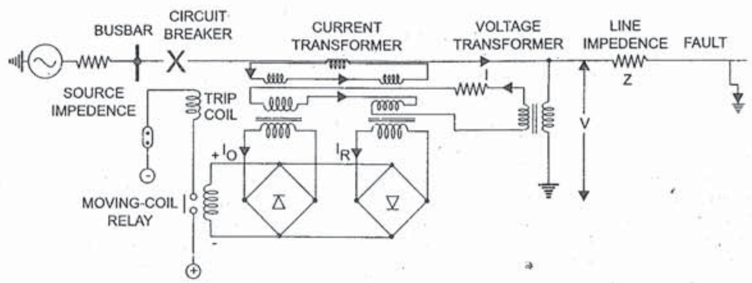


Fig. 42.5. Comparator used as a directional relay.

By use of auxiliary mixing transformer, combination of inputs, replica impedances, dummy impedances input to comparators, a variety of characteristics can be achieved. These are called Mho, off-set mho, elliptical quadrilateral characteristics.

(*iii*) **Offset Mho Relay**

Fig. 42.6 illustrates use of comparator as an off-set Mho Relay. The comparator receives inputs through mixing transformer. The circuit is designed such that the relay operates when V and I have phase angle within certain limits (Directional feature) and ratio V/I is less than a certain value Z_n. However, if direction of power flow is reversed, the phase angle between I and V changes and then the relay operates when ratio V and I is less than KZ_n, which is less than unity. The charac-

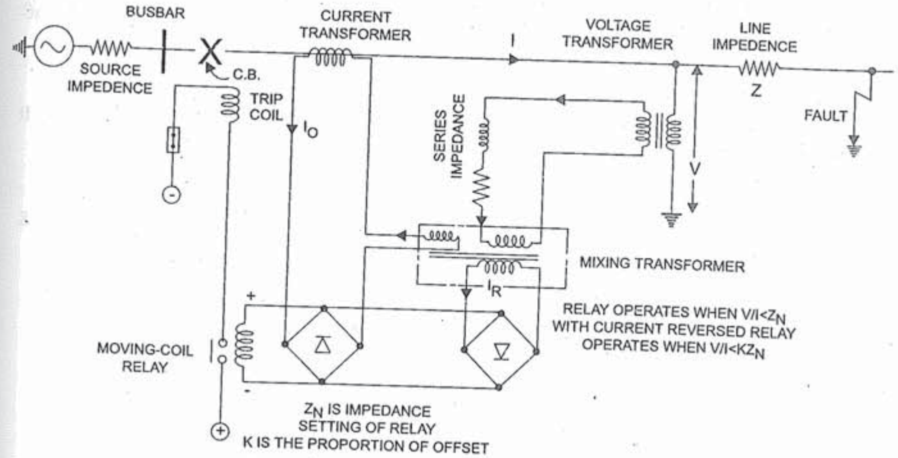


Fig. 42.6. Comparator used as an offset Mho relay. [*Courtesy* : A Reyroll and Co. Ltd., England.]

teristic if such a relay (Fig. 42.7) is called off-set Mho'. On *R-X* plane, it is a circle whose circumference encloses the origin and is slightly offset.

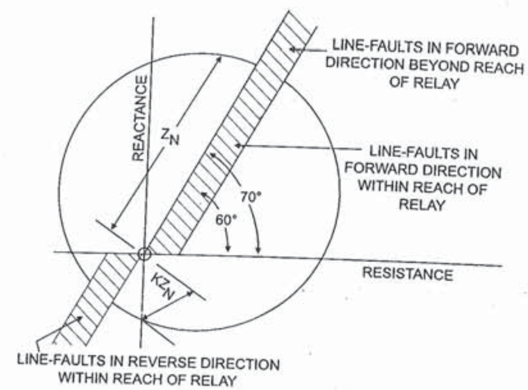


Fig. 42.7. Circle characteristic of offset mho relay. *Courtesy* : A Reyroll & Co. Ltd., England.

Multi Input Comparators

The basic principles of amplitude and phase comparators were described in Ch. 39. In sec. 42.2, we studied comparators having two input.

Distance relays can be either single phase or polyphase and employ multi-input comparators. Such multi-input comparators are either integrating or instantaneous type and compare either amplitude or phase or both.

The characteristic of conventional double input comparators is in form of circles or sectors of circles on R-X plane. Multi-input comparators can have elliptical, conical or quadrilateral characteristic on R-X plane.

42.3. THREE-INPUT AMPLITUDE COMPARATOR

Fig. 42.8 illustrates a current comparator with three inputs. It is an amplitude comparator. It comprises three rectifier-bridges.

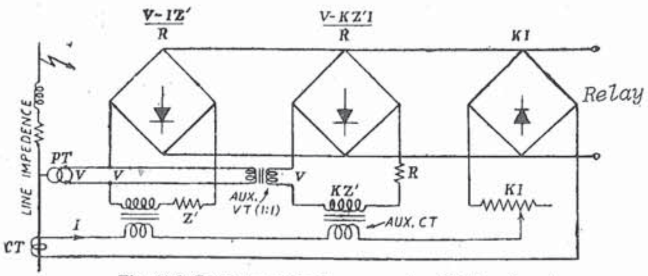


Fig. 42.8. Current amplitude comparator with three inputs giving characteristic Fig. 42.9.

The three bridges get the inputs derived from output VT, CT and mixing transformer. The voltage should be converted into current (Ref. Fig. 42.3). The ultimate characteristic of a particular bridge comparator will depend upon the combination of input circuits. In the circuit under-consideration, the three-inputs are

$$\frac{V - IZ'}{R}, \frac{V - KIZ'}{R} \text{ and } KI.$$

where Z and KZ are replica impedances of same phase angle as that of protected line. The amplitudes currents compared by the bridge are

$$\left|\frac{V - IZ'}{R}\right|, \left|\frac{V - KIZ'}{R}\right| \text{ and } |KI|,$$

the polarity of the bridge of KI being opposite of the other two.

In balance condition, the comparator output is zero.

$$\frac{V - IZ'}{R} + \frac{V - KIZ'}{R} = KI \qquad \text{...(42.1)}$$

where Z' is replica impedance in the relay,

K is the constant to be selected.

Dividing by I, and multiplying by R.

$$\frac{V}{I} - Z' + \frac{V}{I} = KZ' = KR \qquad \text{...(42.2)}$$

But V/I is the impedance of line section measured by the distance relay call it Z

$$(Z - Z') + (Z - KZ') = KR$$

In impedance diagram on $R - X$ plane, Z is the line impedance V/I measured by relay plotted as a characteristic. Whereas Z' is constant replica impedance used in the relay and K and R are constants for a particular setting

$$Z - Z' \text{ is } 0, \text{ as seen later in Eqn. 42.6}$$

rewriting Eqn. 42.3, we get

$$(Z - Z') + (Z - KZ') = KR = 0$$

This is a general equation of the three-input distance relay shown in Fig. 42.8.

The locus of the arrow head of vector Z measured by relay traces a curve on R-X plane by obeying Eq. (42.4).

Obviously the locus will depend on selected values of K, R and Z'.

Suppose, $$K = \left|\frac{Z' - KZ'}{R}\right| \qquad \text{...(42.5)}$$

Substituting in Eqn. (42.4) reduces to

$$|\, Z - Z' \,| + |\, Z - KZ' \,| - |\, Z' - KZ' \,| = 0 \qquad \text{...(42.6)}$$

$$Z - Z' = 0.$$

Which is a plain impedance characteristic, with a circle having centre at origin and radius as Z'

Suppose $k < \dfrac{|\, z' = kz' \,|}{R}$,

Substituting in Eq. (42.4)

$$|\, Z - Z' \,| + |\, Z - kZ' \,| < |\, Z' - kZ' \,| \qquad \text{...(42.7)}$$

The impedance characteristic of Eq. (42.7) is illustrated in Fig. 42.9.

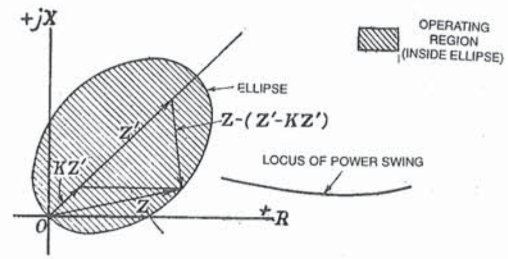


Fig. 42.9. Characteristic of three-input comparator with equation 42.7.

It is an ellipse passing through origin of R-X diagram. The first two terms are distance of foci from the curve and the term on right side is the major diameter.

We will recall that when V/I measured by relay is beyond the characteristic, the relay does not operate. During power swings, the elliptical characteristic with narrow coverage across R axis is less liable for tripping than circular into characteristic.

42.4. HYBRID COMPARATOR

The hybrid comparator compares amplitude and phase. It is a combination of amplitude comparator and phase comparator.

The hybrid comparators are generally multi-input comparators. The three (or more) inputs are derived from output of CT and VT by means of replica impedances, mixing transformers, auxiliary CT's and VT's (Ref. Fig. 42.8 for example)

Two of the inputs are supplied to an amplitude comparator. The output is compared with third input in a phase comparator. Alternatively, two inputs are phase compared and output is amplitude compared with third input.

Refer Fig. 42.10. The phase comparator receives sinusoidal input V and squared input IZ'. The amplitude comparator receives three inputs V, IZ and output of phase comparator $[(V, I, \angle\phi)]$.

The characteristic of Hybrid comparator depends upon the three inputs.

The Fig. 42.10 describes instantaneous relay. There is no integrator in the block diagram.

Example for Practice : Develop a block diagram of a integrating hybrid comparator V and I input. Describe the functioning of the relay.

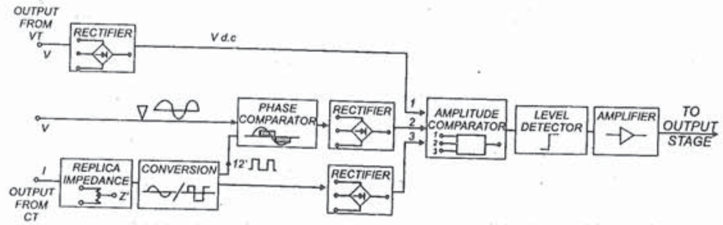


Fig. 42.10. Block diagram of a hybrid comparator used in a Static Distance Relay (Instantaneous Type)

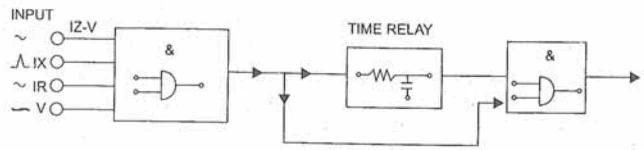
42.5. FOUR INPUT PHASE COMPARATOR WITH QUADRANGULAR CHARACTERISTIC

Ideally, the characteristic of distance relay should overlap the fault area [Fig. 42.11(c)]. In circular characteristic, offered by conventional distance relays, extra area is unnecessarily covered. This makes the relay vulnerable to operate under power swings. With static relays with four-input comparators. It is possible to achieve quadrangular (quadrilateral) characteristic [Fig. 42.11 (b)]. The four-inputs required for quadrangular characteristics are say,

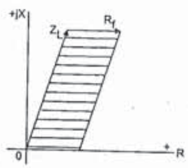
$IZ - V$ .... (Sinusoidal)
IX .... (Pulse)
IR .... (Sinusoidal)
V .... (Sinusoidal)

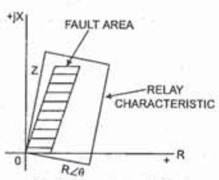
These are given to AND gate

The interaction between IX and V is eliminated by converting one of them into pulses. The delay unit ensures that comparison of all into satisfy the AND condition for the period decided by the delay unit.



(b-1) Block-Diagram.





(a) Z_L = Line Impedance
R_F = Fault Resistance
Fault Area on R-X plane

(b-2) Quadrangular Characteristic
(b) Four-input phase comparator

Fig. 42.11.

42.6. ERRORS IN DISTANCE MEASUREMENT

Distance measurement is affected adversely by the following :

— fault resistance (Ref. Sec. 29.3)
— power swings, hunting
— **double circuit lines**
— bilateral infeed in the protected line
— series capacitors for compensation
— T'eed lines

These problems and their solutions will be discussed in this section.

Distance Measurement : **Impedance as seen by the Distance Relay.**

42.7. INFLUENCE OF POWER SWINGS ON DISTANCE PROTECTION

42.7.1. Power Swings, What are they ?

As we know, a sudden change in the load of a synchronous generator or motor cause oscillations of the power angle about its new equilibrium position, a similar phenomenon occurs in the power transmission through line interconnecting two sources when subjected to a sudden change in the load transfer.

The power transferred through an interconnecting line is given by

$$P \propto \frac{E_1 \cdot E_2 \sin \delta}{X}$$

where P power transfer in watts
E_1, E_2 internal voltages of synchronous machines at sending end and receiving end
δ phase angle between E_1, E_2.

Ref. sec. 44.2 ; the sudden change in loading causes a sudden change in angle δ. Then vectors E_1, E_2 the oscillate between their new equilibrium positions. Thereby, the current vectors at sending end and receiving end also oscillate between their new equilibrium positions. Thus the oscillations are set-up in the voltage and current at sending end and receiving end.

The power transferred through the transmission line is given by

$$P = V_{12} I_{12} \cos \theta$$

V_{12} vector difference between sending end voltage and receiving end voltage.
I_{12} current transferred through the line
θ phase angle between V_{12}, I_{12}
P will be positive at sending end and negative at receiving end.

As the load suddenly changes, vectors E_1, E_2 and vectors V_1, V_2 oscillate, vector V_{12} and I_{12} also oscillate about their respective final equilibrium positions.

This produces power swings which lead to flow of heavy equalizing currents I_{12} between the two ends. Such power swings are more severe when a sudden short-circuit occurs in the sending end station/receiving end station or in transmission line and the circuit-breakers are opened and reclosed. Power swings can occur by disconnection of a large load (one of the outgoing lines or generators).

During power swings, the measurement of V/I performed by distance relays at sending end and receiving end is affected. The distance relay may operate even when there is no fault.

This disturbance at the station busbars affects the neighbouring system and a large zone of the system is subjected to power swings. In Interconnected system where a large proportion of primary protection is by distance relays, this may lead to *indiscriminate tripping at various points in the system,* resulting in cascade tripping and a total black-out. Hence the performance of distance relays and remedial measures under power swing conditions need careful attention.

42.7.2. Effect of Power Swing on the Starting Elements in Distance Schemes.

(Ref. Sec. 30.10, 30.11, 30.13)

The starting elements in distance schemes (Ref. Sec. 30.10) usually respond to either overcurrent or under-impedance.

Overcurrent relays respond to increased current. During power swing conditions, there is a heavy flow of equalizing currents in the transmission lines. Since the phenomenon of power swings is symmetrical, the equalizing currents flow equally in all three phased and cause over-current starting relays of all three phases to pick-up.

The minimum impedance starting relays (Ref. Sec. 30.10) measures V/I. When V/I drops below the setting Z', the starting relay operates. During power swing condition, voltage V drops a certain point of network, equalizing currents increase. Hence minimum impedance starting relays in all three phases operate and remain operates till the power condition persists.

42.7.3. Effect of Power Swing on the Measuring elements in Distance Schemes.

Ref. Sec. 30.10. The *starting element* also called *fault detector* acts first and switches *measuring element* to appropriate input quantity. During power swings, starting elements gets actuated and picked-up as described above and appropriate input quantities are now applied to the measuring elements.

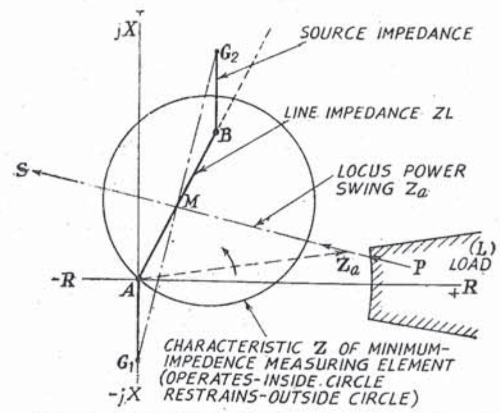
The measuring element should distinguish whether the power swing condition is persisting or not. It should also distinguish whether reduced V/I is due to power swing or a real fault. Usually there is a provision 'blocking'. *Blocking* refers to making the protection scheme in-operative under certain conditions. The measuring elements get blocked during power swings within permissible limits and tripps during faults. In one of the blocking schemes, the measuring element has low output during power swing condition but higher output during fault condition. In another conventional blocking scheme, the blocking unit opens the trip circuit during power-swing conditions.

42.7.4. Representation of Power Swing on R-X diagram

Fig. 42.13 (*b*) represents the source and line impedance on *R-X* plane.

The conditions of a power swing can be represented on a impedance diagram, as shown in Fig. 42.12. For the simplified case of two generators G_1 and G_2 connected by a tie-line impedance Z_L,

(*a*) Two machine system with interconnector *AB*.



(*b*) Representation of source line impedance, apparent impedance on $R-X$ plane (Impedance Diagram)

P_S	Locus of power swing (apparent impedance Z_a		
G_1, G_2	Generating/Motoring sources in two machine system.		
a_2, b_2	Distance relays	A, B	Busbars near a_2, b_2
$G_1 A, G_2 B$	Source impedance'	AB	Line impedance
L	Load impedance	Z_a	Apparent impedance
Z	Characteristic of impedance relay, (Circle).		

Fig. 42.12. Explaining power swings.

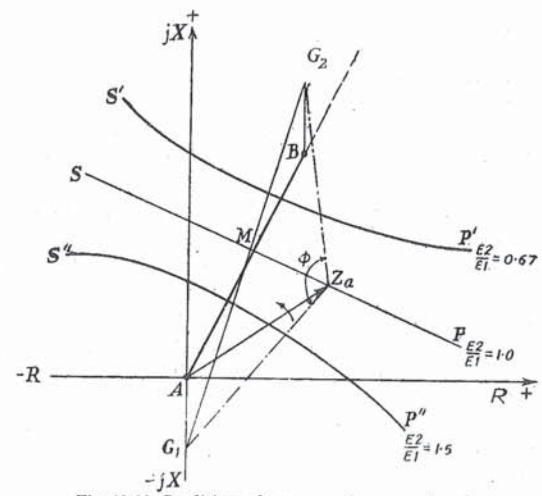


Fig. 42.13. Conditions of a power swing on an impedance diagram. (*R-X* Plane) (Ref. Fig. 42.18).

A	Relay point of near busbars A
AB	Line impedance ZL
A, B	Bus bars
G_1, G_2	Sources in two machine system
$PS, P'S', P''S''$	Locuses of power swing (apparent impedance Z_a)
$G_1 A, G_2 B$	Source impedance
M	Mid of line AB
Z_L	Line impedance
Z_T	Total impedance
Z_a	Impedance seen by relay at A.

the source reactances of the generators and the impedance of the line can be represented on this diagram by the lines $G_1 A$, $G_2 B$ and AB. The point at which relaying is being considered is taken as A, the origin of the diagram. The total impedance Z_r between the generated voltages E_1 and E_2 is represented by line $G_1 G_2$.

Ref. Fig. 42.13. AG_1 and AG_2 represent generator internal reactances on *R-X* diagram. Since generator is predominantly inductive, its resistance is neglected and line AG_1, BG_2 are parallel to X axis. Line AB represents impedance of the transmission line on *RX* plane. Line AG_1 and AG_2 is the total impedance affecting the power swing. The locus of apparent impedance measured by the measuring element during power swing condition is by line *PS* approximately perpendicular to line AG_1 and AG_2 (Ref. Figs. 42.12 and 42.13).

Before the power swing V/I measured by the relay is in area L, far away from the circle Z. During the power swing the apparent impedance seen by the measuring element Z_a varies along with the swing and its locus is along line *PS*.

When the vector Z_a comes inside the characteristic circle-Z, the measuring element operates and relay gets tripped [Fig. 42.12 (*b*)].

Now let us apply the above method of analysis to get the locus Z_a for various ratios of generated voltages.

Remedial Measures to Prevent Operation of Distance Relays under Moderate Power Swing conditions

Under power swing conditions, the point Z_a (apparent impedance seen by the relay at station A) moves from right to left along line PS though there is no fault.

The blocking relay (out-of step relay) operates as the point Z_a touches its circular characteristic. The blocking relay blocks the circuit of the measuring relay for moderate power swing (say angle ϕ between E_1, E_2 upto 260°). As a result, for moderate power swings the distance protection does not operate.

For excessive power swings (say angle ϕ between E_1, E_2 more than 260°). The system is surely going to fall out-of step. In such case the blocking relay unblocks the main measuring relay. If the impedance seen by the main relay is less than the reach impedance, the relay operates.

42.8. PROTECTION OF TEED LINES BY DISTANCE RELAYS

In recent networks, the intermediate switching stations (Ref. Fig. 1.1) are being replaced by Teed Lines (T-off or lines with intermediate current source). The Teed Line with intermediate current feed from the T-off presents a problem in distance measurement.

Refer Fig. 42.15. Consider impedance seen by distance relay a_1 near busbar A. The *true impedance* seen by relay a_1 is the impedance between A_1, F_1 *i.e.* $Z_A + Z_B$. In absence of intermediate line T_C, the relay a_1 with measure this impedance.

With intermediate current infeed I_2, the situation changes. The apparent impedance seen by relay a_1 becomes

$$Z_T = Z_A + Z_B + \frac{I_2}{I_1} Z_B.$$

This being more than true impedance $(Z_A + Z_B)$ the fault appears to be farther away from actual location because of the mutual impedance effect due to current I_2, given by the third term on right hand side.

When current I_2 flows in intermediate Teed Line, the relay at station A will *under-reach, i.e.* protect less length of line that desired. (Since distance relay operates when Z_T is less than the relay setting Z_A and the Teed Line increases Z_r).

Because of the intermediate current in feed through Teed Line the distance relay from A does not protect the original length of line, for condition without the intermediate infeed.

Suppose, the high speed distance relays at a_1 is set to protect 80% of line AB. Suppose fault F is at 80% length of line AB, the relay a_1 will clear it when I_2 is zero but will not clear it if I_2 is present.

Hence the setting of relay at station A should be done by considering effect of intermediate infeed I_2. *It is practice to adjust the distance relays to operate as desired on the basis of no intermediate current infeed.* The fault F at the boundary of the first zone (say 80% of, AB) will not be seen by the first zone of relay a_1 but will be within the second zone of relay a_1. Second zone of relay a_1 covers complete AB plus part of line beyond AB but takes more time corresponding to the second step (Ref. Sec. 30.12)

42.9. BACK-UP PROTECTION WITH INTERMEDIATE INFEED

Consider back-up protection in distance protection scheme. This was described in Sec. 30.12 and Fig. 30.12. Now refer Fig. 42.15.

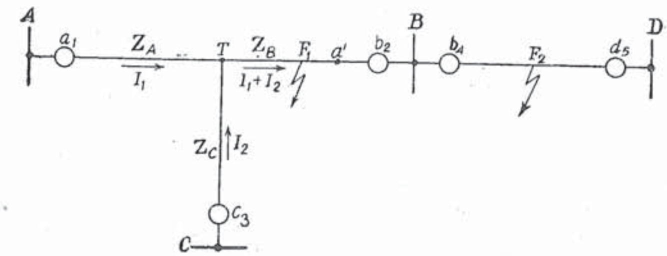


Fig. 42.15. Explaining effect of intermediate current source on distance measurement.

A, B, C, D	Busbars in different station
a_1, b_2, c_3, d_s	Distance Relays near A, B, C, D respectively
F_1, F_2	Faults
Z_A	Impedance between A, T
Z_B	Impedance between T, F
Z_C	Impedance between C, T
T	Point of Tee-off.

For a fault F_2 between B, D ; b_4 gives primary protection and relay a_1 gives back up. If breaker of b_4 fails to clear, breaker of a_1 should clear as a back-up. With intermediate infeed from C, the setting of relay a_1 for relay b_4 is a problem similar to that discussed in Sec. 42.10.

The fault F_2 should be *normally* in the second or third step of relay a_1 and first step of relay b_4. However, with the intermediate infeed from C, the fault F_2 is seen by relay b_4 as farther away and also by relay a_1 as farther away towards or beyond D. In extreme cases the apparent impedance seen by relay a_1 for fault F_2 may be beyond its third step and relay a_1 may not be sense the fault F_2 (Refer Fig. 30.12). Hence back-up protection by distance protection needs readjustment for lines with intermediate infeeds.

One solution to this problem is 'reversed third zone' by mho type distance relay with directional comparison type carrier current pilot relaying (Refer Sec. 30.14.2).

42.10. COMPENSATION OR COMPOUNDING IN DISTANCE RELAYS

Refer Sec. 30.10. Distance scheme has several measuring elements and starting elements. The response of the starting elements must be as fast as that of measuring elements so the speed of measuring elements is fully exploited. The minimum impedance relays (relays which operates for value of Z below its setting) operate when V/I measured by the relay is less than its setting.

The voltage V seen by the relay from the secondary side of VT is influenced by several aspects such as

— type of fault, *e.g.*. *L-G, L-L, 2L-G*.
— location of fault, whether near the measuring point or far away.
— VT connection with the relay.

The minimum impedance relays operate for reduced value of V and increased value of I. In EHV systems, particularly for single line to ground fault at the end of the line, these conditions are often not satisfied. In such case the relay does not operate and compensation or compounding is necessary compensation can be voltage compensation or current compensated.

"Compensation refers to feeding an additional input quantity in addition to main input quantity for the purpose of correction in performance characteristic. The additional input quantity supplements the main input quantity and provides compensation for measurement errors.

Consider voltage compensation (Ref. Fig. 42.8). The voltage comparator is supplied with phase voltage at its location and also phase voltage of the same phase compounded to about 70% of the line length. This compensation may be in the form of an replica impedance in voltage circuit of comparator to prevent input being effective until the desired value is reached.

For example the relay may operate with vector products of the two voltages (main and compensation) is less than the set value. When fault occurs at the remote end of line, the drop in only main voltage may not cause operation but the combined drop of main and compensating voltages may be enough.

Compensation may also obtained by introducing compensating current to the comparator of relay (Ref. Fig. 42.5). With current compensation, the relay may operate for lesser voltage (V/I remaining same). However, this compensation may not be preferred as it has to operate for very low voltages where accuracy is affected by other stray disturbances.

Section III. EXAMPLES ON SETTING OF DISTANCE RELAYS

42.11. SETTING OF DISTANCE RELAYS

We will now study the setting of impedance relay and mho relay for given line parameters. The *R-X* diagram is a powerful tool for analysis. The line characteristic and relay characteristic are drawn on the same *R-X* diagram.

We will recall that the line impedance is on the primary side of CT and VT, whereas the distance relay is on secondary side. To superimpose the line characteristic on relay characteristic both should be referred to the same side, preferably the secondary side. The following are the guidelines :

1. System quantities V and I should refer to the same phase corresponding the relay of that phase, *e.g.*, for earth fault protection of phase R, the voltage and current of phase R will be sensed by relay.
2. Voltage and current should be considered from the location of VT and CT.
3. Co-ordinates of *R-X* diagram must be in the same units (ohms).
4. Per unit system is preferred for large systems. Direct ohmic method may be used in simple problems.
5. Phase angles are important.
6. Both line characteristic and relay characteristic is referred to secondary sides and plotted on the same *R-X* diagram.

Conversion from Primary to Secondary Side

Line impedance on primary side is seen by the relay through CT and VT. The actual ohms of primary side should be converted to secondary side as seen by distance relay. This conversion is by means of a simple expression given below.

$$\boxed{Z_s = Z_p \times \frac{\text{CT ratio}}{\text{VT ratio}}}$$

where Z_s = Impedance as referred to secondary side of CT and VT and as seen by relay, ohms.

Z_p = Line/system impedance in ohms.

The same expression applies to R and X.

42.12. SOLVED EXAMPLES ON DISTANCE RELAY SETTING

Example 42.1. *Given. Line Impedance*

$Z_L = 2.5 + j5.0$

CT Ratio = *400/1*

VT Ratio = *33,000/110*

(*a*) *Plot line characteristic on R-X* plane referred to secondary side.

(*b*) *Plot characteristic of minimum impedance relay to protect 80% of the line length on same* *R-X* plane neglecting arc resistance.

(*c*) *Plot characteristic or mho relay having 45° maximum torque angle, to protect 80% of the line length, indicate the regions of operation and non-operation on the R – x diagram.*

Solution

(*a*) **Plain Impedance Relay** (Refer Fig. 42.16)

Line Impedance (given)

$$= 2.5 + j5 \text{ (Primary)}$$

i.e. $$Z_{L\,Primary} = 5.6 \angle 63.5° \text{ (Primary)}$$

Line impedance seen by relay through CT and VT is given by the equation.

$$Z_{L\,secondary} = Z_{1\,primary} \times \frac{\text{CT ratio}}{\text{VT ratio}}$$

$$= 5.6 \times \frac{400 \times 110}{33{,}000} = 7.47\ \Omega \text{ Secondary}$$

Draw on *X-R* plane line *AB* equal to 7.47 ohms at an angle $\theta = 63.5°$ with reference.

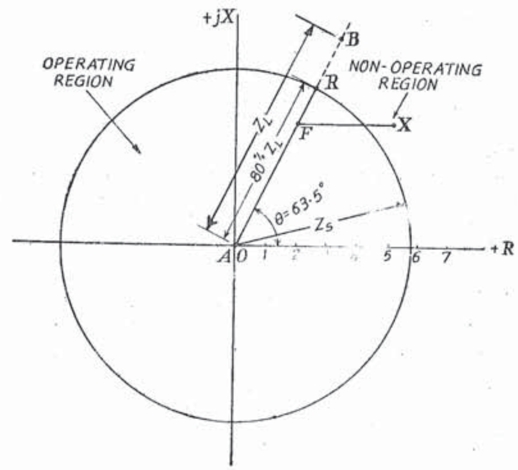
The setting of distance relay is such that it protects 80% of the line. Mark point R on line *AB* such that

AR should be reach of plain impedance relay. Hence setting of plain impedance relay Z_s is given by

$$A_s = AB \times \frac{80}{100} = 7.47 \times \frac{80}{100} = 5.98, \text{ ohms.}$$

Characteristic of impedance relay is a circle with origin O at A, radius AR = 5.98 ohms.

The relay operates for fault on transmission line between $A - R$ which lie within the circle.



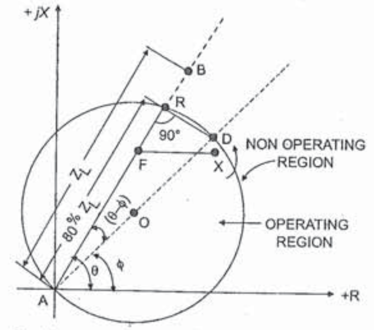
Z_L = 7.47 ohms (secondary)
Z_S = 5.98 ohms (secondary)
Z_F = 2.43 ohms (secondary)

AB line impedance Z_L seen from A
θ angle of line impedance
AF line impedance of 80% length from A, (Ex. 42.2)
AR impedance of 60% length from A
O origin of impedance circle coincides with A

Fig. 42.16. (Example 42.1 *a*) Line characteristic and plain impedance relay setting on *R-X* plane.

(*b*) **Mho-relay** (Refer Fig. 42.17)

Draw line AB and point R as in case a. The mho characteristic is different from impedance characteristic. mho characteristic is a circle passing through the centre of R-X plane and with axis along line of maximum torque.



Note : $(\theta - \phi) = \dfrac{AR}{AD}$

FX	Fault resistance (secondary)	AB	line impedance Z_L seen from A
AR	impedance of 80% length of line from A	$\theta°$	line angle 63.5°
ϕ	maximum torque angle of Mho relay = 45°	AD	relay setting
O	origin of Mho-circle mho circle passes through A.		

Fig. 42.17 (Example 42.1 *b*). Line characteristic and Mho-relay setting on R-X plane.

Draw line AD, line of maximum torque at angle ϕ equal to 45° (given).

Draw a circle passing through points A, R with AD as axis. Point D is fixed as follows :

$$\cos(\theta - \phi) = \frac{AR}{AD}$$

$$AD = \frac{AR}{\cos(\theta - \phi)} = \frac{5.98}{\cos(63.5° - 45°)} = \frac{5.98}{0.948} = 6.32 \text{ ohms.}$$

Hence setting AD of mho relay = 6.32 ohms. The circle of mho characteristic with this setting passes through A and R (Refer Fig. 42.17).

Example 42.2. Effect of Fault Resistance. *Consider the plain impedance relay and mho relay as set in Example 42.1 for protection 80% of line AB. Given a symmetrical phase to phase fault at F at a distance 60% from A. Fault resistance is 20 ohms. Indicate the fault point on R-X diagrams* and state whether the relays operate or not.

Solution. Convert fault resistance for secondary side.

$$\text{Fault Resistance Secondary} = \text{Fault Resistance Primary} \times \frac{\text{CT Ratio}}{\text{VT Ratio}}$$

$$= 2.0 \times \frac{400}{1} \times \frac{110}{33{,}000}$$

$$= \frac{8}{3.0} = 2.6 \text{ ohm (Secondary)}$$

Indicate point F on line AB at 60% of AB

$$AF = \frac{60}{100} \times 7.47 = 4.49 = 4.5\ \Omega.$$

Draw FX parallel to R axis.

$$Fx = 2.6 \text{ ohms (Fault Resistance)}$$

Refer Fig. 42.16 and Fig. 42.17.

From Fig. 42.16, the point X is outside the circle. Hence plain impedance relay does not operate. (Under-reach : reads less impedance).

From Fig. 42.17, the point X is inside the circle. Hence Mho type distance relay operates.

Conclusion

1. The mho characteristic provides margin for the arc resistance than the plane impedance characteristic.

2. The area of mho characteristic being less than the impedance characteristic, the mho characteristic gives better stability.

Example 42.3. Setting of a Distance Relay. *A 110 kV of 35 km length is protected by Impedance Relay. The first stage of distance relay protects 90% of the line. Calculate the setting of impedance relay and draw the characteristic of line and the relay on R-X plane. Neglect the influence of arc resistance.*

The line impedance is 0.24 + j 0.41 ohms per conductor per km.

CT ratio is 300/1 A and VT ratio is 100 kV/100V.

Solution. Line impedance

$$= 0.24 + j0.41 \text{ ohm/km.}$$

Line angle (Refer Fig. 42.16)

(Assumed the same for phase faults and earth fault).

CT ratio $= 300/1 = 300$

VT ratio $= 100{,}000/100 = 1000$

Step 1. Calculate line impedance referred to secondary

$$Z_s = Z_p \times \frac{\text{CT Ratio}}{\text{VT Ratio}}$$

For 90% line of 35 km length,

$$Z_p = 0.9 \times 35 \times (0.24 + j0.41).$$

$$= 7.56 + j12.9 \text{ ohms per conductor}$$

$$Z_s = (7.56 + j12.9) \times \frac{300}{1000}$$

$$= 2.268 + j3.87 \text{ ohm secondary.}$$

Step 2. Impedance Diagram (Refer Fig. 42.16 for guidance). Draw a line AB at an angle $\theta = 60°$ to R axis. Plot point R at $R = 2.268$ and $jX = 3.87$.

Draw a circle with centre O at A and radius $AR = \sqrt{(2.268)^2 + (3.87)^2}$. This circle represents characteristic of a plain impedance relay to protect 90% of the line.

QUESTIONS

1. With the help of neat sketches describe the principle of a current comparator and a voltage comparator used in distance protection.
2. Discuss the use of multi-output comparators in static distance protection. Explain how oval and quadrilateral characteristics can be obtained on R-X plane.
3. With the help of a block diagram explain the functioning of a static distance relay.
4. In a distance protection scheme, the line CT has a ratio of 300/1 A, the line VT has a ratio of 33,000/110 V. The line impedance is $0.24 + j0.41$ ohm per conductor per km. Length of line is 25 km.

   Draw R-X diagram indicating the line characteristic with reference to secondary.

   Indicate the circle of plain impedance characteristic to protect 80% length of line (Neglect fault resistance).

5. Indicate on an R-X diagram, the following (select suitable scale, point A at $(0, J\ 0)$.
   (a) Point $R = 1\ \Omega\ jX = +3$
   (b) Point $R = 1, jX = -1$
   (c) Line impedance $AB = 2 + j4$
   (d) Fault resistance at the end of line AB equal to two ohms.
   (e) Mho characteristic with maximum torque angle 53° and radius 3 ohms.
   (f) Plain impedance characteristic to protect 80% of line AB

   Explain the advantages of Mho-characteristic over the plain impedance characteristic. Quantities given refer to secondary side.
6. **Power-Swings.** Explain with the help of neat sketches the phenomenon of power swings in transmission system with particular reference to its influence on distance measurement.

   Describe the blocking features adopted in distance relays to offer selective blocking under power swing conditions.
7. **Lines with series Capacitor.** State the function of series capacitors in long transmission lines. Discuss the difficulties in distance measurement with application of series capacitors. Explain the effect of series capacitor on impedance characteristic drawn on R-X plane. Explain the remedial features provided in distance relay schemes to protect such lines.
8. Explain the following (any two)
   (i) carrier acceleration
   (ii) carrier blocking
   (iii) mho characteristics
   (iv) directional mho characteristics
9. Discuss the errors in distance measurement in double-in-feed lines. State the remedial measures in distance protection schemes for such lines.
10. Explain the requirements of distance protection schemes of long EHV transmission lines. State the merits of static distance relays. Illustrate the features of any static distance relay by means of simplified block-diagram.
11. Explain effect of intermediate infeed from a Teed line on the distance measurement of transmission line.

43-A

Important Assorted Topics and Static Protection Schemes

Insulation, Reliability, Testing
Electrical Noise — Shielding — Guards — Grounding — Over-voltages — Protection — Reliability — Tests for reliability.
Static Protection Schemes
Static protection of Medium Motors and Large Motors — Static Protection of Busbars — Disconnection of Mains Supply by Static Schemes.
Back-up protection, Centrally Coordinated Back-up, protection Signalling
Breaker Back-up — Use of Microprocessor — Computer based centrally coordinated Back-up Programmable Equipment for relaying, protection and control — Principle of centralized back-up — Post fault control — Communication Links for protection signalling — Digital Message System — Fibre Optic Data Transmission.

INSTALLATION, RELIABILITY AND TESTING OF STATIC RELAYS

43.1. COMBATING ELECTRICAL NOISE AND INTERFERENCES

Any disturbing signal which interferes or disturbs the electronic measurement/signal/parameters is electrical noise. All electronic circuits and their installations should be with the noise below acceptable level. This is very important for accurate functioning and reliability of static relay functioning. Conventional electromagnetic relays do not have such a problem. Relaying and control installations for static devices should be designed with particular attention to noise and transient over voltages. The effect of noise and transient over-voltages is two-fold.

(i) error in measurements (ii) maloperation.

The noise can be caused by the following :

— Interfering external signals in the form of electromagnetic radiation or waves, *e.g.* solar waves, radio waves from transmitting stations, electromagnetic waves caused by sudden current changes in a remote electrical circuit, a passing electrical locomotive may cause an error in electrical measurement, a radio voice is distorted by interference from neighbouring station, switching of high voltage line sends a electromagnetic radiation, sparking or corona discharge at a remote point causes disturbance in sensitive voltage measurement.

— Lightning and Switching Surges on primary side of CT's and VT's get reflected on secondary in form of voltage spikes.

— Drifts in electronic apparatus beyond their limit of stability.

— Imperfect connections of fixed wires or connectors leading to minute sparking. Corrosion/wear/imperfection of working joints.

— Device noise depending upon characteristic of resistors, capacitors, semi-conductors as affected by temperature, humidity, loading.