CHAPTER IX

RESTRICTED ZONE PROTECTION OF SHORT TRANSMISSION LINES

9.1 INTRODUCTION :

Short transmission lines are usually protected by means of differential relays which employ the principle of ' Unit Protection ' . Pilot-wires are used to facilitate the exchange of information about the system on either side of the protected section. The experience with electro-mechanical relays in this mode of protection is extensive and circulating current and balanced voltage schemes, utilising amplitude comparison, are successfully employed in practice[58,59,60,61]. Further, the attenuation and the phase-shift of the signals transmitted over the pilot-wires are analysed and the methods of their compensation are also reported[53].

The amplitude comparison techniques hitherto employed introduce errors in the comparison. Further the time of operation of the relays is also considerably large due to the inertia of the moving parts of the relays. The static relays employing phase comparators, though over-come these limitations, do not, however, provide an adequately large zone of simultaneous tripping of the breakers on either side of the line when employing simple 'stable zone ' in the form of a circle[55,56]. As discussed in the previous chapter although the stable zones employing larger number of discontinuities help in reducing the region of sequential tripping they pose difficulties in the formation of measuring circuits to derive the required signals for the phase comparison.

A novel scheme of protection of short transmission lines, called ' Restricted Zone Protection ' reported by Kliman[43], over-comes to a large extent, the above mentioned short comings of the conventional and recently developed differential protection schemes. In this scheme the difference of positive sequence voltages at the two ends of the protected line section is compared with the positive sequence current at the local end, the positive sequence voltage of the remote end being obtained by means of the pilot-wires. The comparison is carried out in an impedance unit, and the mode of protection essentially terminates into that of distance measurement. In this reference (43), the criterion for the discrimination of the internal faults from through faults and healthy conditions of the system is established. Further, a circular 'stable-zone', with radius about 0.1 Z(Z being the impedance of the transmission line under consideration) is suggested. The analysis, however, employs the only comparison as mentioned above and restricts to the scalar valuesof the relaying current distribution factor. Further the attenuation and the phase shift of the signals transmitted over the pilot circuits are not taken into account.

In the present chapter, therefore, two schemes of the comparison are considered and analysed, taking into account the complexity of the relaying current distribution factor, and the propagation of the signals transmitted over the pilot-wires. Further, the equations of the power swing loci are developed from the fundamental considerations and the swing loci are plotted on the impedance plane to appreciate their effects upon the relay performance. The shape of the ' stable zone ' is discussed on the basis of this analysis and finally static comparator models are developed to realise the required stable zones.

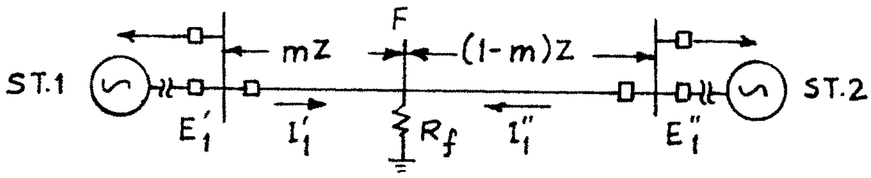
9.2 SCHEME 1 :

9.2.1 Analysis :

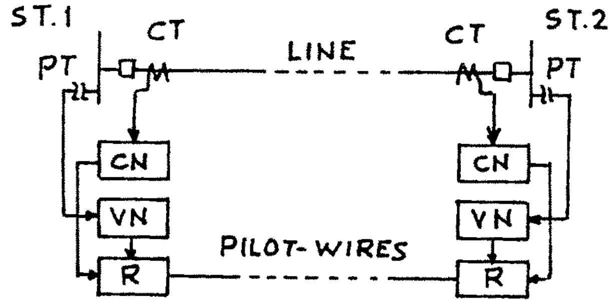
In this scheme the two end voltages are compared with the local end current.

Basic Equations :

Fig.9.1(a) shows a typical power system and 9.1(b) the scheme employed for the protection of the transmission line. The relay at end-1 is supplied with the positive sequence voltages e_1' and e_1'' and the positive sequence current i_1' such that it measures the impedance



(a) A TYPICAL POWER SYSTEM



(b) SCHEME OF PROTECTION

FIG. 9·1 A TYPICAL POWER SYSTEM AND SCHEME OF PROTECTION

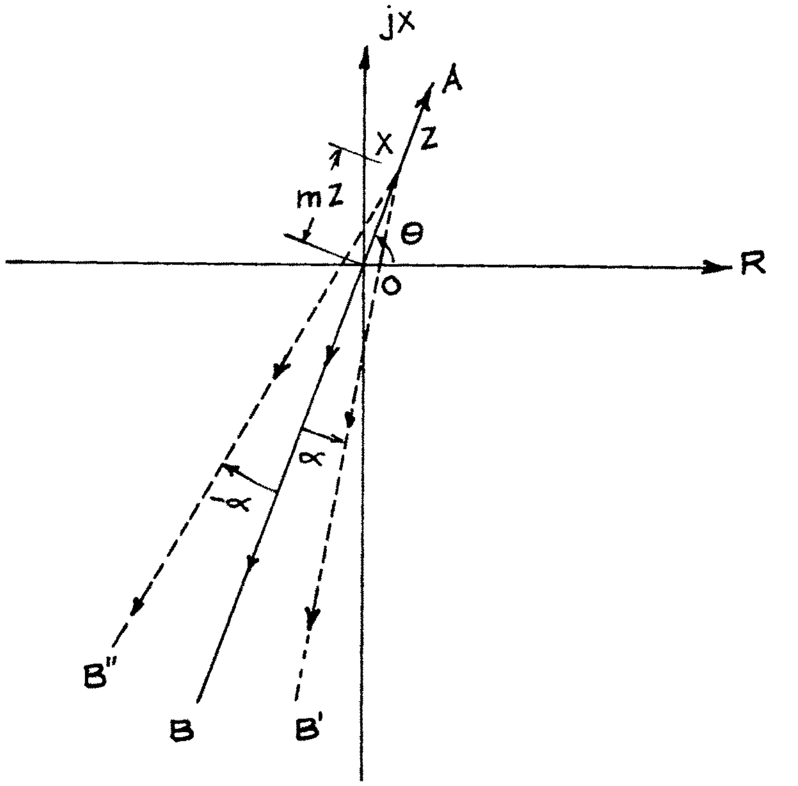


FIG. 9·2 IMPEDANCE LOCI WITH $K = k_1 \angle \alpha$; $\gamma = 1\angle 0$

$$Z'_{r_1} = \frac{\Delta e'_1}{i'_1}$$

$$= \frac{e'_1 - e''_1}{i'_1}$$

$$= \frac{E'_1 - \gamma E''_1}{I'_1} \qquad \text{.... (9.1)}$$

Where γ is the propagation constant taking into account the attenuation and phase shift in E''_1, when it is relayed over the pilot wires.

From fig.9.1(a) it is evident that the positive sequence voltages E'_1 and E''_1, at bus 1 and bus 2 respectively, will be given by

$$E'_1 = I'_1 mZ + (I'_1 + I''_1)R_f \qquad \text{..... (9.2)}$$

$$E''_1 = I''_1 (1-m)Z + (I'_1 + I''_1)R_f \qquad \text{.... (9.3)}$$

Where R_f is the fault resistance.

If K is defined as a relaying current distribution factor, given by

$$K = \frac{i''_1}{i'_1} = \frac{I''_1}{I'_1} \qquad \text{.... (9.4)}$$

and introduced in eq.(9.2) and (9.3) and finally equations (9.2) and (9.3) substituted in (9.1), the impedance seen by the relay will become

$$Z'_{r_1} = Z\left[m + \gamma K(m-1)\right] + R_f(1+K)(1-\gamma) \qquad \text{....(9.5)}$$

A similar expression for the impedance seen by the relay at station 2 can also be derived.

Eq.(9.5) is the general expression for the impedance seen by the relay at station 1 and takes into account the attenuation and phase shift of E_1''. The individual effects of these factors on the impedance measurements will now be considered.

ATTENUATION AND PHASE SHIFT IGNORED :

If one ignores the effect of attenuation and phase-shift of E_1'' and substitutes $\gamma = 1\angle 0$ in eq.(9.5), the expression for Z'_{r_1} will reduce to

$$Z'_{r_1} = Z\,[\,m + K(m-1)\,] \qquad \ldots. (9.6)$$

Eq.(9.6) will now be used to find the impedance measured by the relay at station 1 under different conditions of the system.

Through Faults and Healthy Conditions :

For the case of through faults and healthy conditions of the system, the currents at the two ends of the protected transmission line section will be equal on account of the negligible capacitance of the protected line. Substituting, therefore, the value of $K = -1$ in eq.(9.6) the latter, gives the impedance seen by the relay at station 1 as ,

$$Z'_{r_1} = Z \qquad \ldots. (9.7)$$

Internal Faults :

For the internal faults the value of m will be less than 1. The factor K may assume any value from 0 to ∞ . For K to be a scalar factor the locus of Z'_{r_1} will be the line BX of fig.9.2 . Line OX represents the value of m on impedance vector Z and the arrow on BX shows the direction of the impedance seen by the relay for increasing values of K.

If K is treated as a complex factor $K_1 \angle \alpha$, then the locus of Z'_{r_1} will shift from XB to XB' or XB'' depending upon the positive or negative values of α . It may be noted that the maximum value of the impedance seen by the relay for particular value of m will be mZ, irrespective of the value of K. For fault on bus 2, the impedance seen by the relay at station 1, will be equal to the line impedance.

From the above analysis it may be concluded that the point $Z\angle\theta$ on the impedance plane represents the conditions of the fault on bus 2 and the through faults and healthy conditions of the system. For internal faults, the impedance measured by the relay will have a value less than Z .

EFFECTS OF ATTENUATION AND PHASE SHIFT :

If the effects of attenuation and phase-shift are to be considered in the analysis, then γ must be retained in eq.(9.5). For a particular pilot-wire system under consideration, the value of γ will be fixed and can be found following the procedure outlined in the Appendix.

Healthy Condition of the System :

It is evident that on retaining the value of γ, eq.(9.5) cannot be employed for this case. Removing the fault point of fig.9.1 and considering Z_x as the impedance viewed from bus 2 in the direction of the flow of power, following expressions for E_1' and E_1'' can be written :

$$E_1' = E_1'' + I_1' Z$$

and $$E_1'' = I_1' Z_x \qquad \ldots. (9.8)$$

The impedance seen by the relay will then become,

$$Z'_{r_1} = \frac{E_1' - \gamma E_1''}{I_1'}$$

$$= Z + Z_x(1 - \gamma) \qquad \ldots. (9.9)$$

Since $\gamma \leqslant 1$, the impedance seen by the relay has a value greater than Z for $\gamma \neq 1$. The departure of the value of Z'_{r_1} from Z will obviously depend upon Z_x and γ.

Through Faults :

Again it is evident that eq.(9.5) cannot be employed for analysing this case. Power system representation of fig.9.1 is, therefore, modified and shown in fig. 9.3. The impedance measured by the relay at station 1 will be

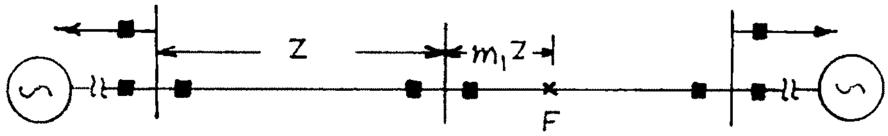


FIG. 9.3 A TYPICAL POWER SYSTEM FOR CONSIDERATION OF EXTERNAL FAULTS

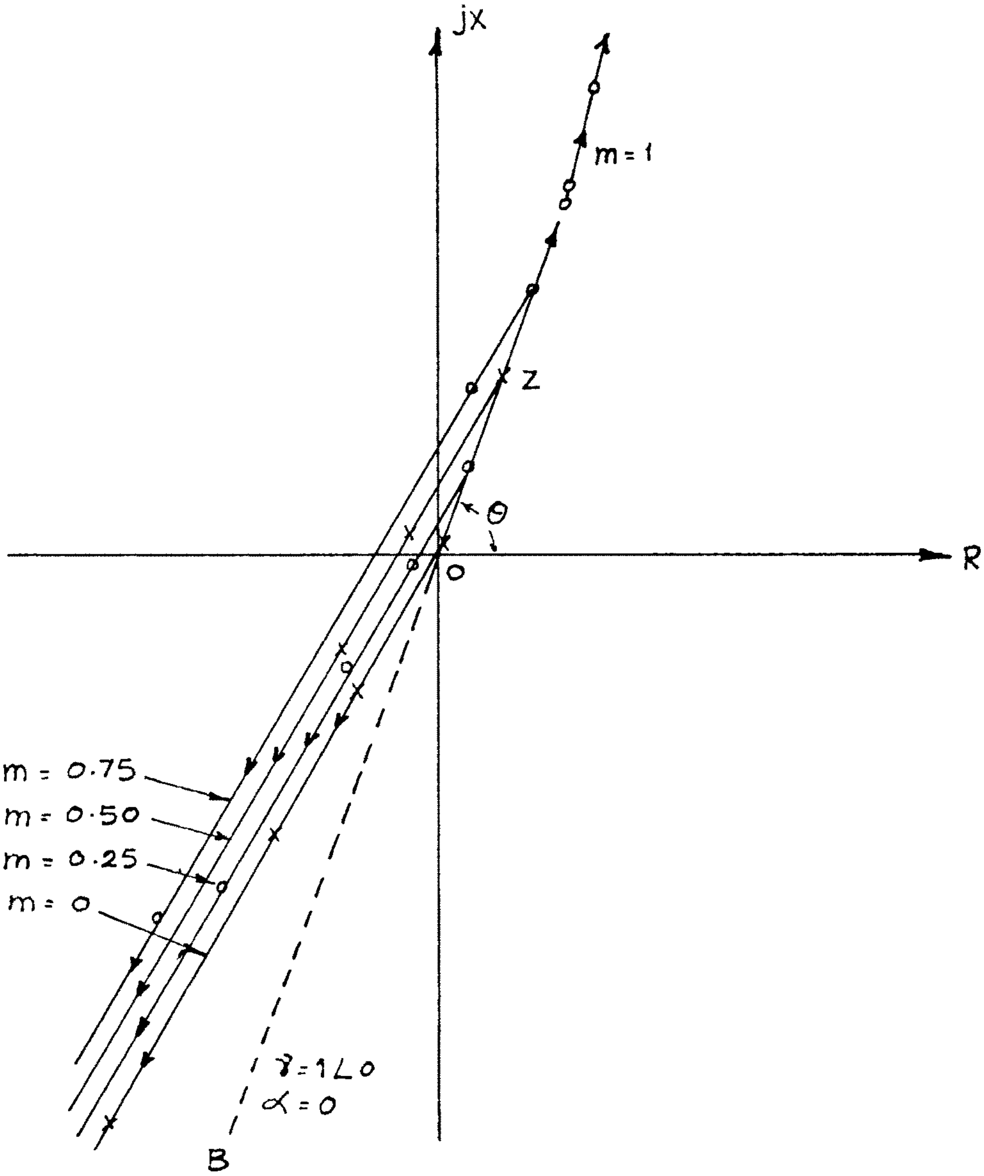


FIG. 9.4 IMPEDANCE LOCI WITH $\gamma = 0.95\angle -10^\circ$; $\alpha = 0$

$$Z'_{r_1} = \frac{\Delta e'_1}{i'_1}$$

$$= \left[(Z+m_1 Z) + \frac{E_{1w}}{I'_1} \right] - \gamma \left[m_1 Z + \frac{E_{1w}}{I'_1} \right]$$

$$= Z\left[1+m_1(1-\gamma) \right] + \frac{E_{1w}}{I'_1}(1-\gamma) \qquad \ldots. (9.10)$$

where E_{1w} is the positive sequence voltage at the point of fault. It is clear from eq.(9.10) that under the through fault conditions, Z'_{r_1} will be greater than Z ; since $m_1 > 0$. The departure of Z'_{r_1} from Z will depend upon the values of m_1 , γ and E_{1w} .

<u>Internal Faults</u> :

For this case it is necessary to employ eq.(9.5) to find the values of Z'_{r_1} for various values of γ ,m,K and R_f. A typical value of $\gamma = 0.95 \angle -10^{\circ}$ and $R_f = 0.2\,|Z|$ is chosen and substituted in eq.(9.5). Factor K is assumed to be real and varied from 0 to ∞ , m being the parameter. The impedance loci so obtained are plotted in fig.9.4 .

It may be noted from fig.9.4 that the effect of γ is two fold : (i) to some extent it increases the value of Z'_{r_1} and (ii) for different values of m, the impedance loci shift from the line OB . There will be a further shift of the impedance loci, by an angle α , if K is treated as complex.

It may further be noted that for faults on bus 2 the impedance measured by the relay at station 1 will have a value greater than Z.

9.2.2 P-ower Swing Equation :

For the derivation of power swing equation a two-machine system is drawn in fig.9.5. E_A is the voltage back of transient reactance Z_A of machine 1 and E_B is the voltage back of transient reactance Z_B of machine 2.

Let E_B be the reference vector . The current in the series circuit is, then given by

$$I' = \frac{E_A \angle\delta - E_B \angle 0}{Z_A + Z_B + Z} \quad .... (9.11)$$

where δ is the load angle which varies. The impedance seen by the relay during this condition of the system will be given by

$$Z'_{r_1} = \frac{E_A\angle\delta\ [Z_B(1-\gamma) + Z] + E_B\angle 0\ [Z_A(1-\gamma) - \gamma Z]}{E_A\angle\delta - E_B\angle 0} \quad .... (9.12)$$

For the investigation of the effect of power swings on the mode of protection, the system is assumed to be homogeneous.

End Voltages Equal :

If the magnitudes of the emfs E_A and E_B are assumed to be equal then eq.(9.12) reduces to

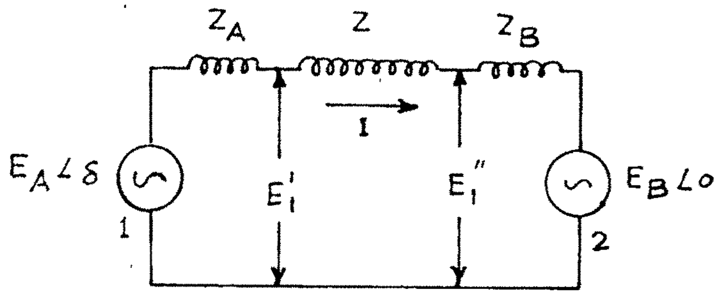


FIG.9-5 A TWO-MACHINE SYSTEM

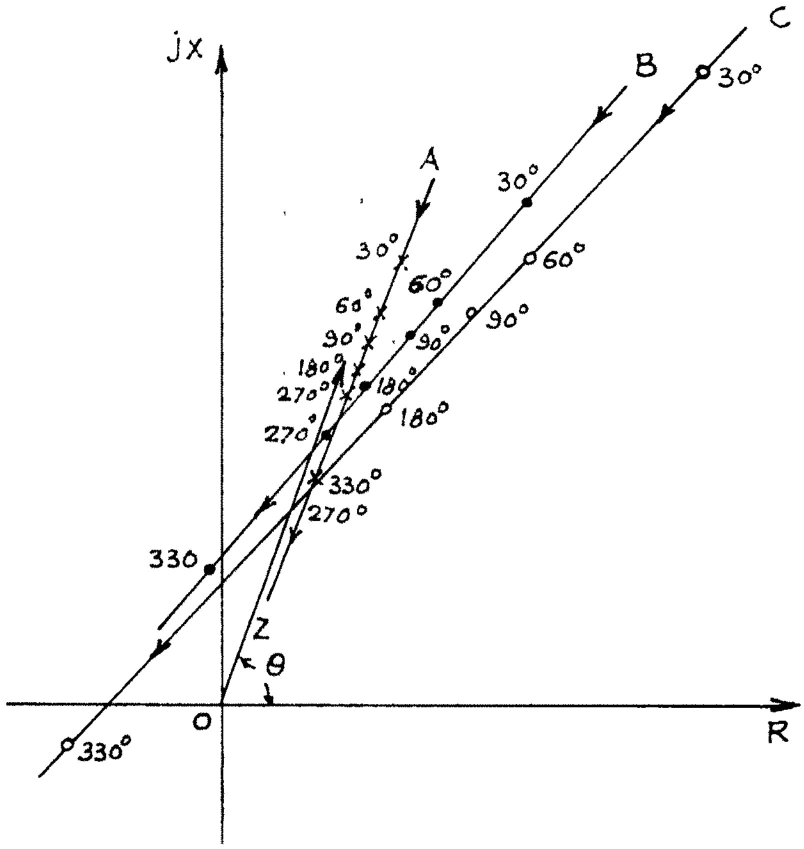


FIG.9·6 POWER SWING LOCI FOR VARIOUS VALUES OF γ

$p = q = 0{\cdot}5$

(A) $\gamma = 1{\cdot}0\angle -5^\circ$

(B) $\gamma = 0{\cdot}95\angle -10^\circ$

(C) $\gamma = 0{\cdot}92\angle -20^\circ$

$$Z'_{r_1} = \frac{Z[1\angle\delta\,\{q(1-\gamma)+1\} + \{p(1-\gamma)-\gamma\}]}{1\angle\delta - 1\angle 0} \quad \text{.... (9.13)}$$

where $p = Z_A / Z$ and $q = Z_B / Z$.

With typical values of p,q and γ, power swing loci are calculated and plotted in fig. 9.6 through fig. 9.9 .

End Voltages unequal :

To determine the effect of γ on power swing loci with unequal voltages at the two ends of the protected line section, eq.(9.12) is modified as ,

$$Z'_{r_1} = \frac{Z\,[\,C\angle\delta\,\{q(1-\gamma)+1\} + p\{(1-\gamma)-\gamma\}\,]}{C\angle\delta - 1\angle 0} \quad \text{.... (9.14)}$$

where $C = |E_A| / |E_B|$

For various values of p,q, γ and C swing loci are calculated and plotted in fig.9.10 through fig. 9.12 .

9.2.3 The Shape Of The Stable-Zone :

From the analysis of section 9.2.1 and 9.2.2 it is clear that, for the values of $\gamma = 1\angle 0^{\circ}$ the impedances seen by the relay under through faults, power swings and healthy conditions of the system are very nearly equal to Z . However, the relay measures impedances less than Z for the internal faults. A circular stable zone of fig.9.13

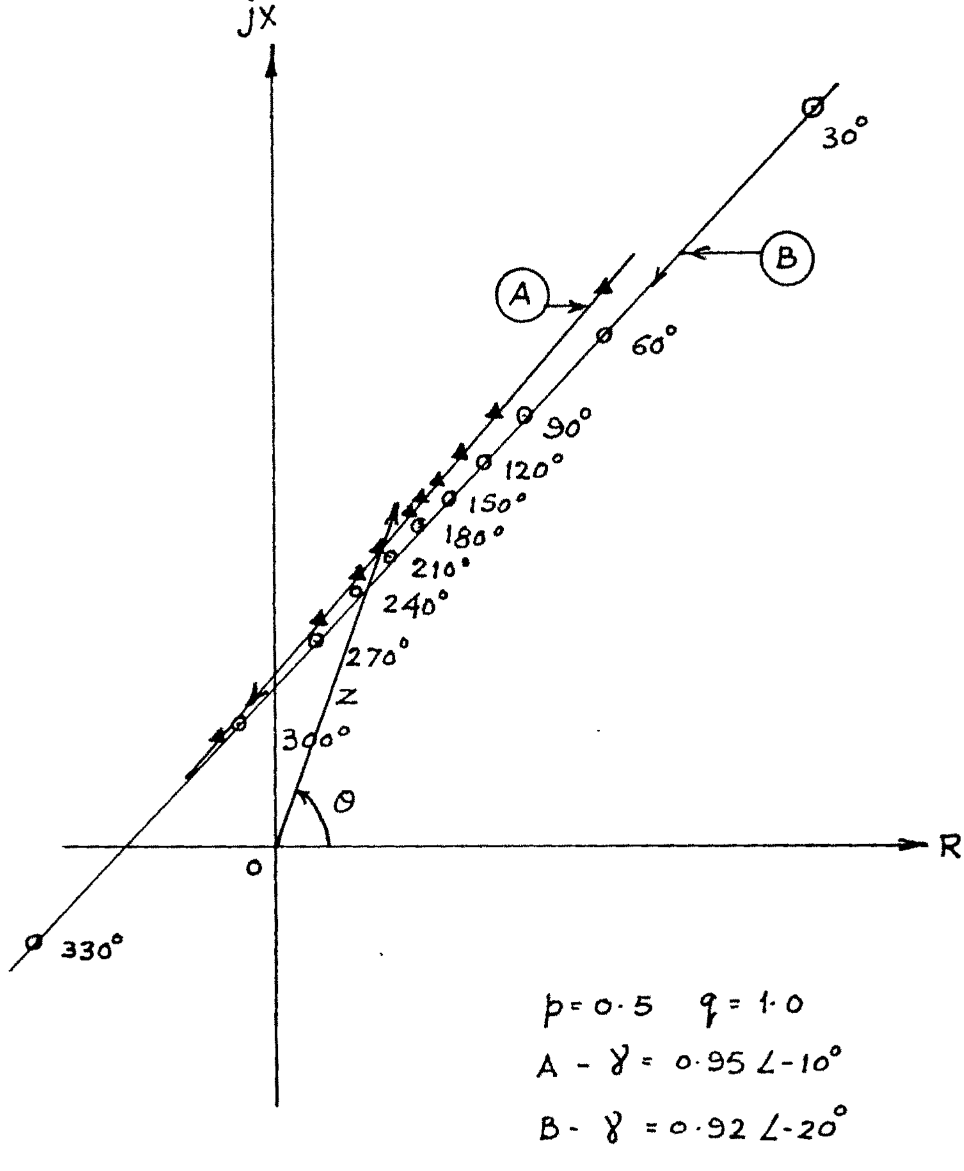


FIG. 9.7 POWER SWING LOCI

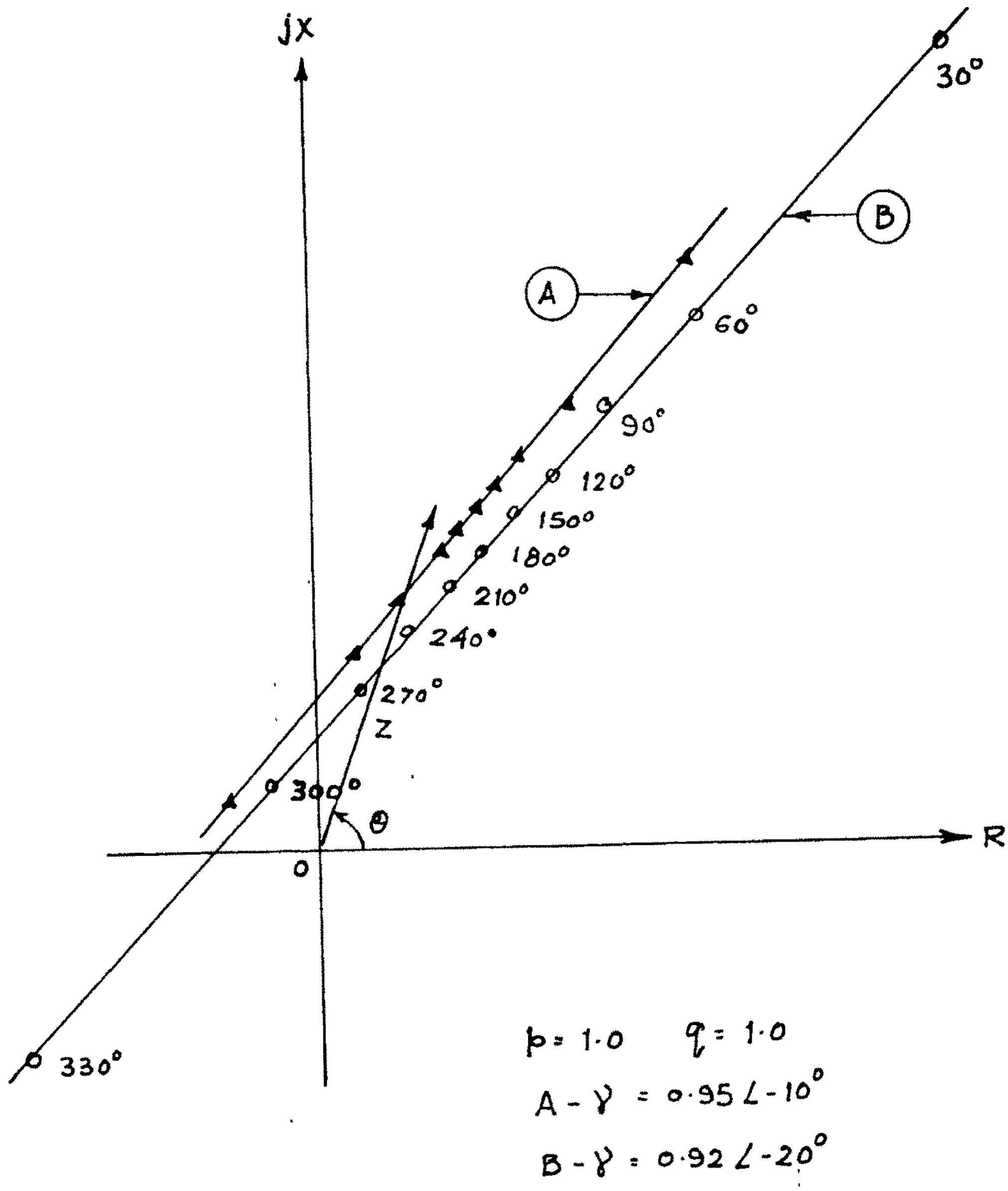


FIG. 9·8 POWER SWING LOCI

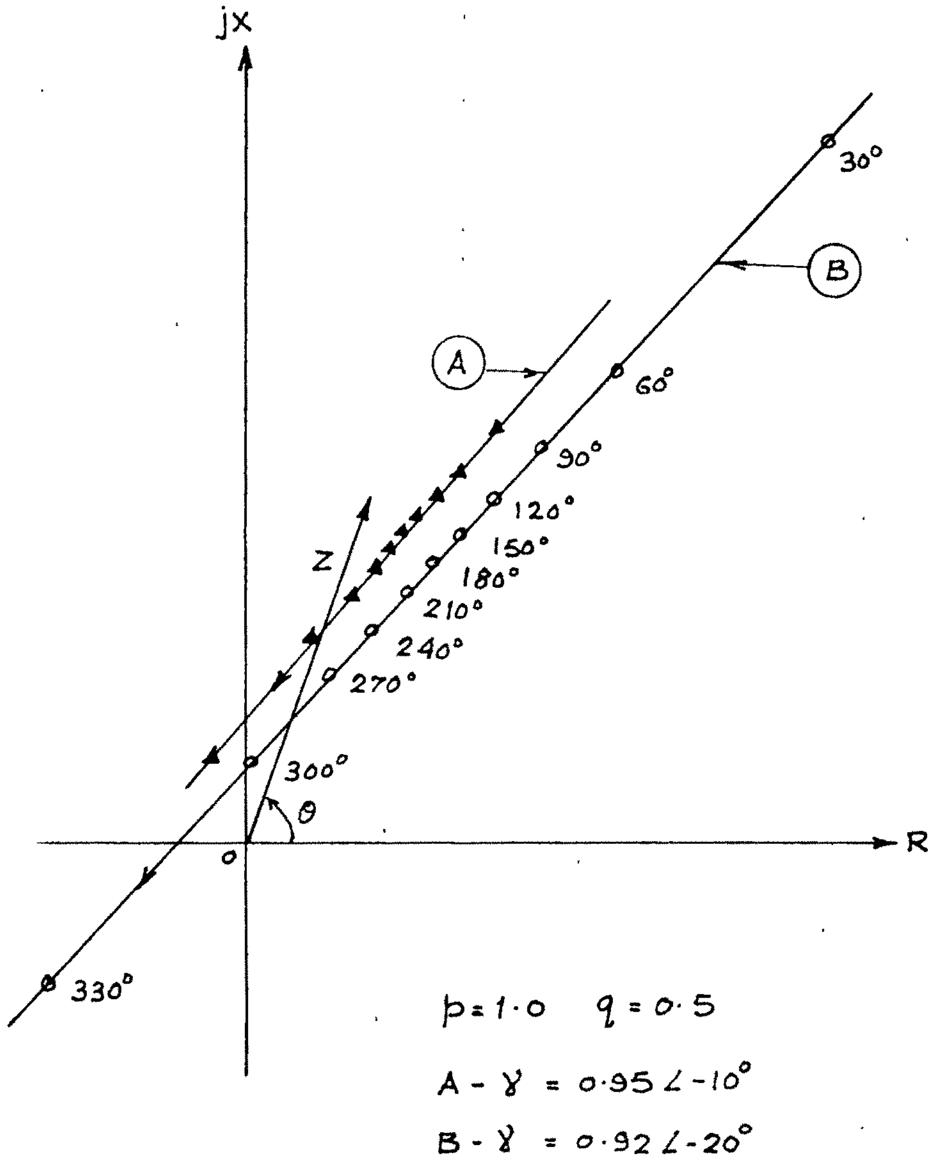


FIG. 9·9 POWER SWING LOCI

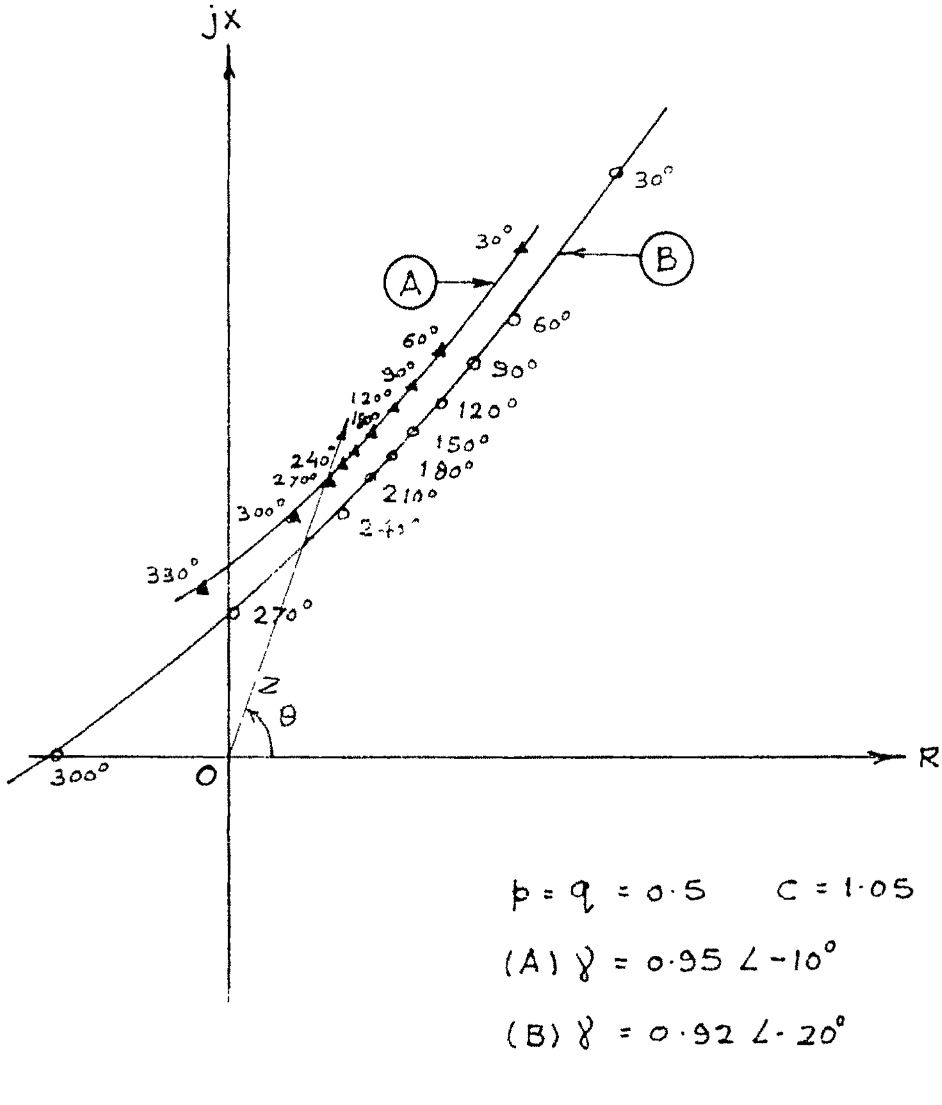
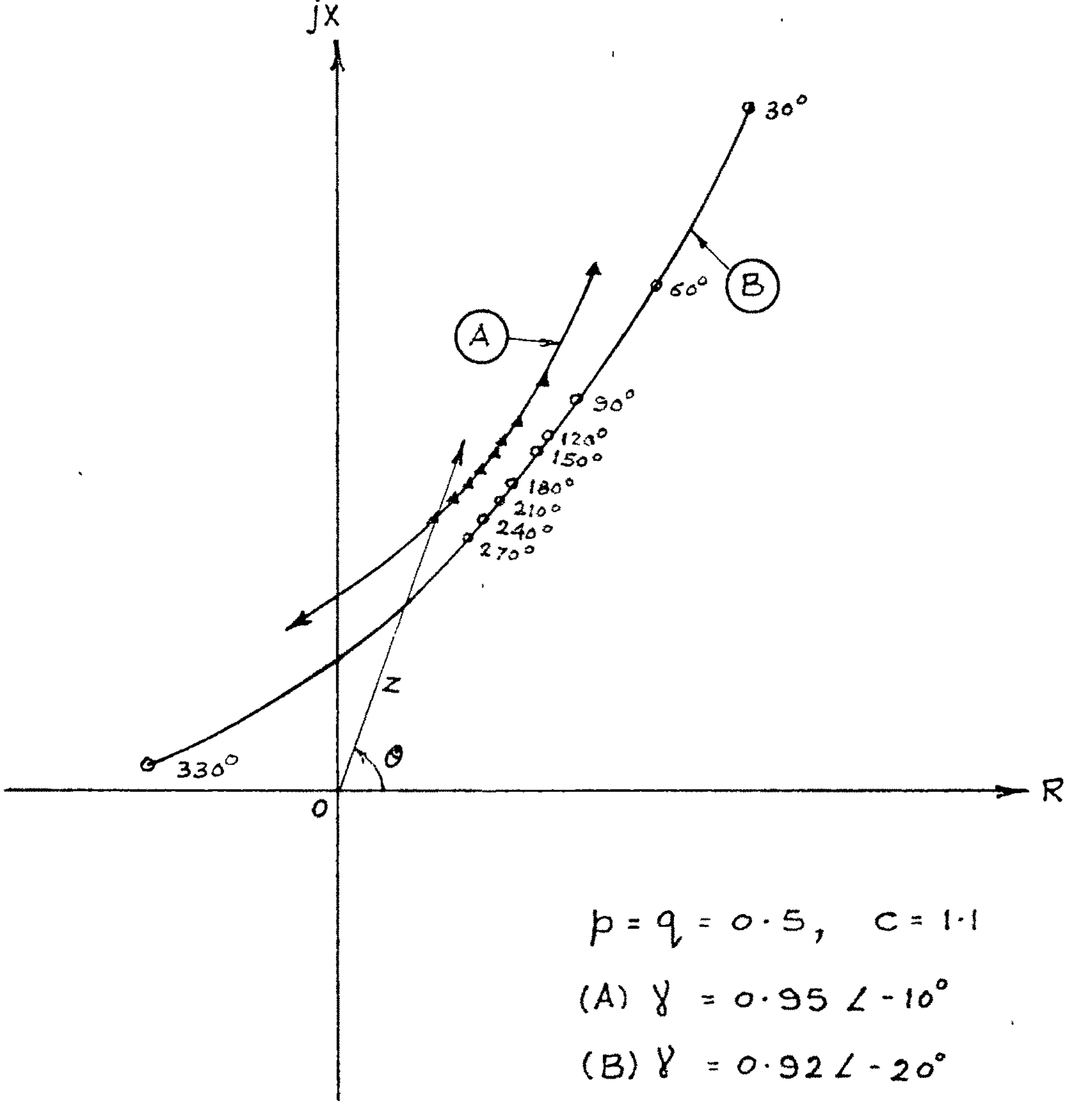


FIG. 9·10 POWER SWING LOCI



$p = q = 0.5, \quad c = 1.1$

(A) $\gamma = 0.95 \angle -10^\circ$

(B) $\gamma = 0.92 \angle -20^\circ$

FIG. 9·11 POWER SWING LOCI

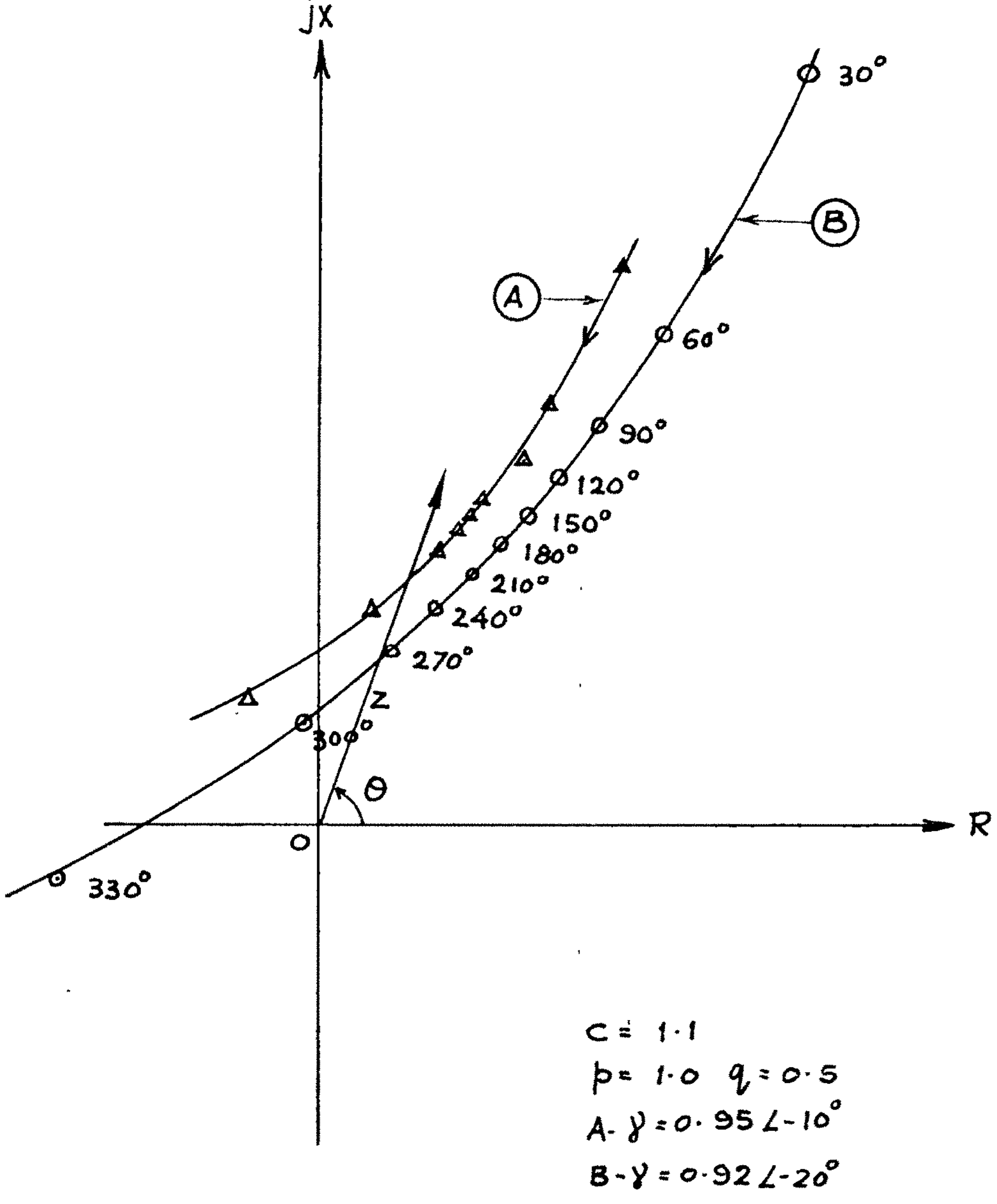


FIG. 9·12 POWER SWING LOCI

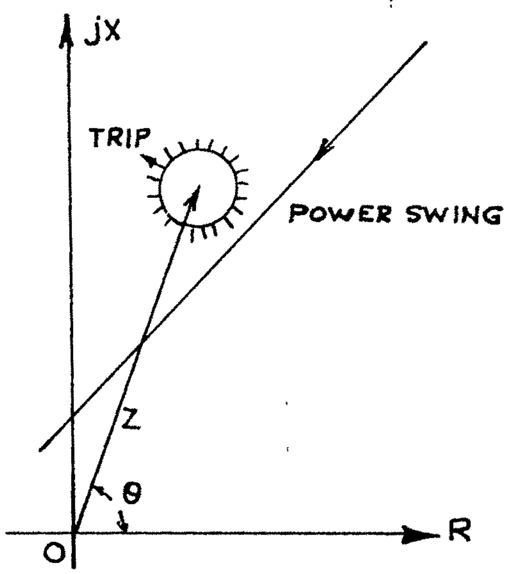


FIG. 9·13 CIRCULAR STABLE ZONE

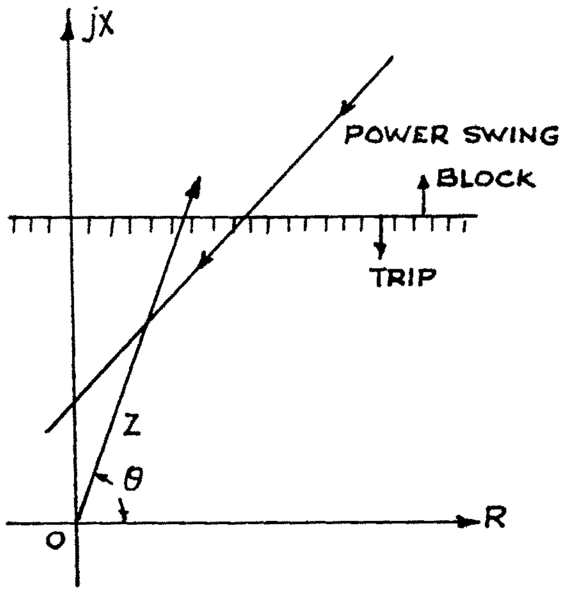


FIG. 9·14 REACTANCE CHARACTERISTIC

may, therefore, be employed as suggested in reference(43). This characteristic will be more immune to sequential tripping of the circuit breakers.

However, when γ assumes a value other than $1\angle 0$, the impedance vectors seen by the relay shift upward on R-X plane. This may be taken care of by increasing the radius of the circular stable zone . However, the increase in radius will increase the area of the zone of sequential tripping. Further, even during less severe power swings, from which the system is likely to recover, the relay will have a tendency to trip the breakers. Under these conditions, therefore, the circular stable zone of fig.9.13 cannot be employed unless the pilot-wires are perfectly compensated. A little departure from perfect compensation will render the relay vulnerable to power swings.

A possible alternative is to employ the reactance characteristic of fig.9.14 . This characteristic appears to provide a better stable zone. Further, the relay will not trip the breakers during less severe power swings from which the system is likely to recover. The additional advantages of this characteristic are as follows :

(i) This characteristic can be easily employed for back-up protection.

(ii) This characteristic does not provide a larger area for sequential tripping since all the impedance vectors under internal fault conditions are to lie below the reactance characteristic only. The blocking region above the point $Z \angle\theta$, therefore, does not form part of the sequential tripping region.

It is evident from the above analysis that the relay is not fully immune to power swings in that for very severe power swings the relay has a tendency to trip the breakers.

9.3 SCHEME 2 :

In this scheme the relay at end 1 is supplied with e_1' from the local end and i_1'' from the remote end, i_1'' being obtained over the pilot circuits. Both e_1' and i_1'' are the positive sequence quantities.

9.3.1 Analysis :

Fig.9.15 illustrates the scheme of comparison for the protection of the system of fig.9.1(a) .

Basic Equations :

The relay at end 1 is supplied with e_1' and i_1'' such that it measures ,

$$Z'_{r_1} = \frac{e_1'}{-\gamma i_1''} = \frac{E_1'}{-\gamma I_1''} \qquad \text{.... (9.15)}$$

The propagation constant γ takes into account the attenuation and phase shift of the relayed signal. The positive sequence voltage E_1' at bus 1 can be written from

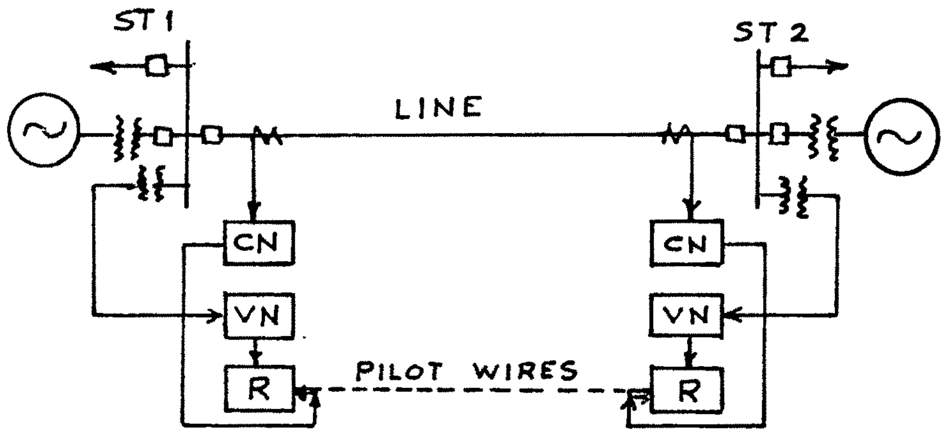


FIG. 9·15 SCHEME OF PROTECTION

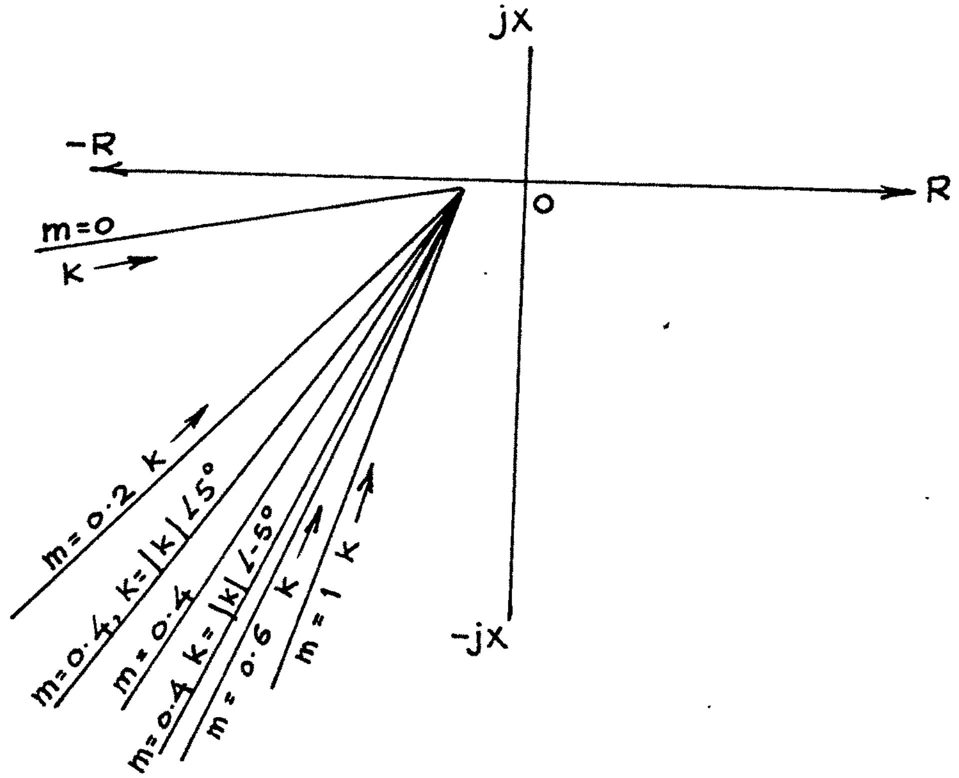


FIG. 9·16 INTERNAL FAULTS ON IMPEDANCE PLANE fig.9.1(a) as ,

$$E'_1 = I'_1 mZ + (I'_1 + I''_1)R_f \qquad \text{.... (9.16)}$$

On substituting the relaying current distribution factor in eq.(9.16), the latter reduces to

$$Z'_{r_1} = - \left[\frac{mZ + R_f(1+K)}{\gamma K} \right] \qquad \text{.... (9.17)}$$

Internal Faults :

To consider the internal fault condition of the system eq.(9.17) must be employed. With typical values of $Z = |Z| \angle\theta$, $R_f = 0.2\ |Z|$, and $\gamma = 0.95 \angle -10^{\circ}$ the impedance loci are calculated for different values of m with K as a parameter. These loci are plotted in fig.9.16 . The effect of considering K as a complex factor is also shown in the figure.

Healthy Condition :

The healthy condition of the system can be expressed by

$$E'_1 = I'_1 Z_L \qquad \text{.... (9.18)}$$

where Z_L takes into account the line and load impedance under normal condition as seen from end 1. Here K assumes a value -1 and the impedance seen by the relay reduces to ,

$$Z'_{r_1} = \frac{Z_L}{\gamma} \qquad \text{.... (9.19)}$$

Fig.9.17 illustrates the impedance seen by the relay on the impedance plane in accordance with eq.(9.19) .

Through Fault Condition :

The through fault is external to the protected zone and can be expressed by

$$\left.\begin{aligned} E_1' &= I_1' Z + E_1'' \\ E_1'' &= I_1' Z_X \end{aligned}\right\} \qquad \text{.... (9.20)}$$

The expression for impedance seen by the relay at station 1 reduces to ,

$$Z_{r_1}' = \frac{Z + Z_X}{\gamma} \qquad \text{.... (9.21)}$$

It is evident that the impedance seen by the relay is greater than Z by an amount equal to Z_X . The through fault condition is illustrated in fig.9.17 .

9.3.2 Power Swing Equation :

The expression for power swing can be obtained by considering once again the two-machine system of fig.9.5 . With E_B as the reference vector, the current in the series circuit will be given by eq.9.11. The impedance seen by the relay at station 1 during this condition of the system will be

$$Z_{r_1}' = \frac{(Z + Z_B)\, E_A \angle\delta + Z_A E_B \angle 0}{E_A \angle\delta - E_B \angle 0} \qquad \text{.... (9.22)}$$

End Voltages Equal :

If the system is assumed to be homogeneous with

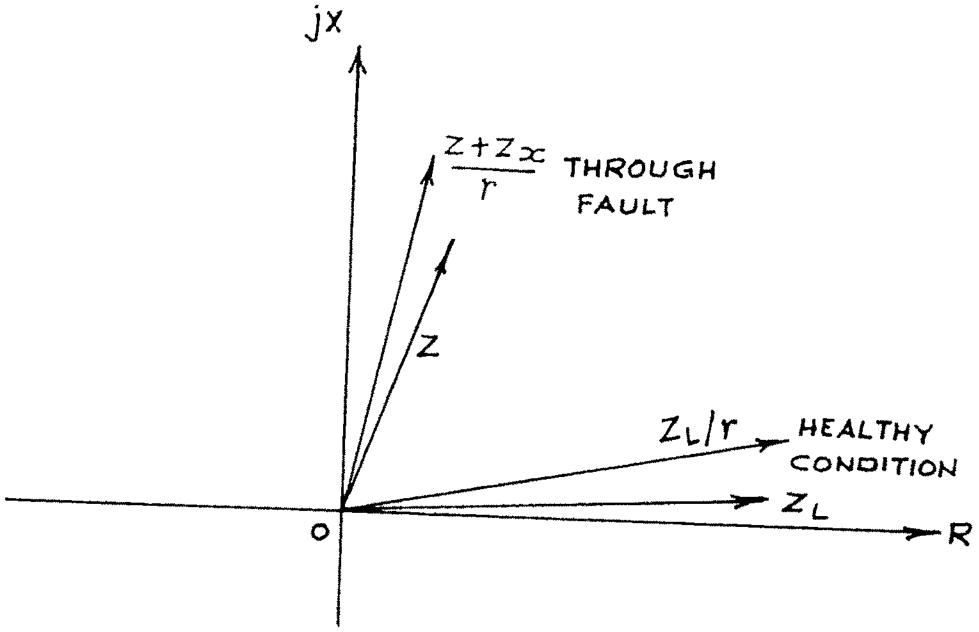


FIG. 9·17 THROUGH FAULT AND HEALTHY CONDITION magnitudes of E_A and E_B equal, then eq.(9.22) will reduce to

$$Z'_{r_1} = \frac{Z}{\gamma}\left[\frac{(1+q)\angle\delta + p\angle 0}{(1\angle\delta - 1\angle 0)}\right] \qquad \ldots. (9.23)$$

Where $p = Z_A / Z$ and $q = Z_B / Z$.

With typical values of $p = q = 0.5$, the swing loci for different values of γ are calculated and plotted in fig. 9.18.

End Voltages Unequal :

To investigate the effect of unequal voltages on the power swings, eq.(9.22) is modified and written in eq.(9.24)

$$Z'_{r_1} = \frac{Z}{\gamma}\left[\frac{(1+q)\angle\delta + C\,p\angle 0}{1\angle\delta - C\angle 0}\right] \qquad \ldots. (9.24)$$

With a typical value of C along with the values of p,q and γ the swing locus is calculated and plotted in fig.9.18 .

9.3.3 Shape Of The Stable Zone :

The fundamental requirement for satisfactory protection characteristic is that a reliable margin of discrimination shall exist between healthy and external fault conditions on one hand and those corresponding to the faults internal to the protected zone on the other.

The analysis presented in the previous section clearly shows the discrimination between the internal fault condition

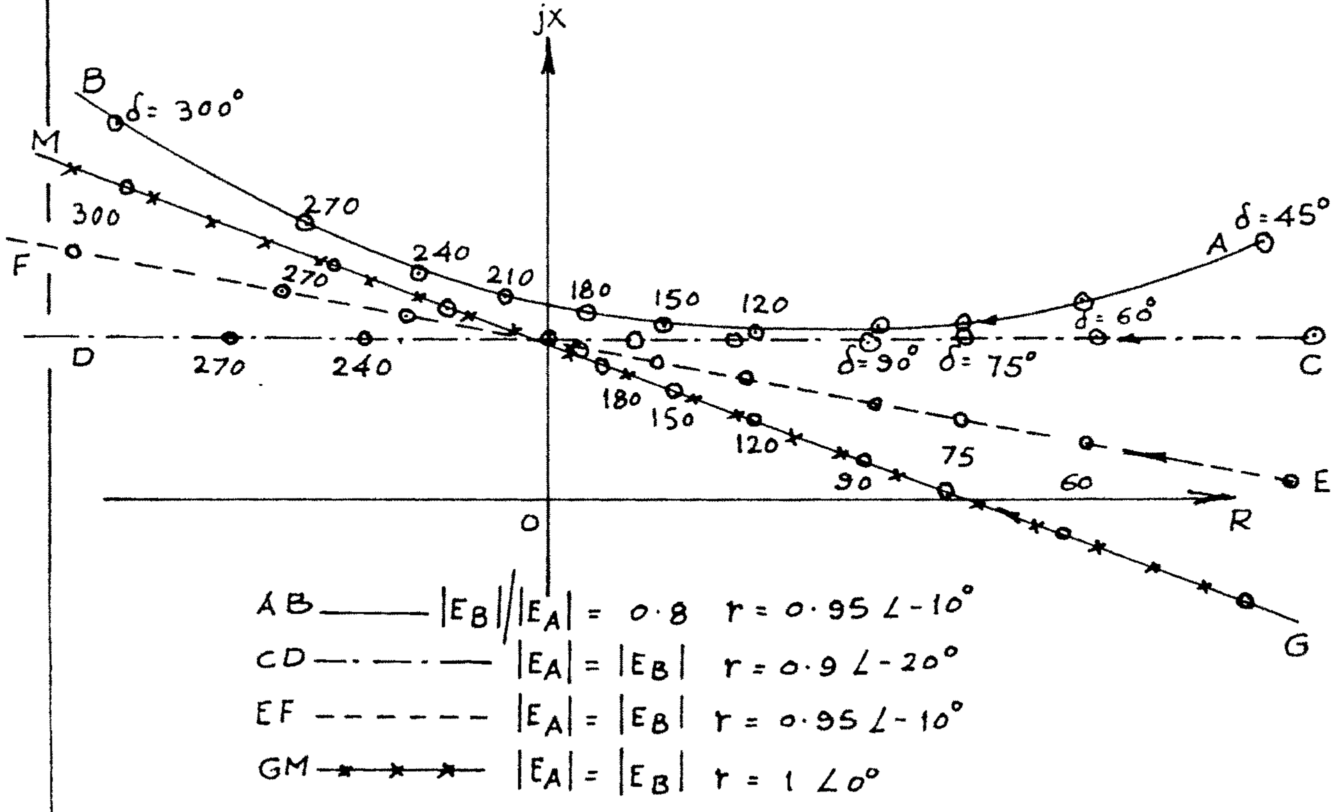


FIG. 9·18 POWER SWING LOCI

and the other conditions of the system.

With this consideration the desirable characteristic is the one given in fig.9.19 . It is evident that this characteristic will make the relay trip only during internal fault conditions rendering the latter fully immune to power swings. Further, since the complete section is possible to be protected with this characteristic in the instantaneous operation the zone of sequential tripping is practically eliminated.

9.4 RELAY CIRCUITRY :

To obtain the desired characteristics discussed in section 9.2 and 9.3 the necessary relay circuitry will now be described .

9.4.1 Scheme 1 :

As explained in section 9.2 the desired characteristic is the reactance characteristic of fig.9.14. This characteristic can be easily obtained by employing phase comparator utilising sine comparison techniques discussed in chapter 3.

Fig.9.20 illustrates the block schematic diagram of the relay. e and i are applied to the positive sequence voltage, and current networks respectively. e_1' and i_1' so obtained are applied, along with e_1'' , to the measuring circuits which produce the required signals $-S_1$ and S_2 . S_1 and S_2 given by eq.9.25 are the required signals to

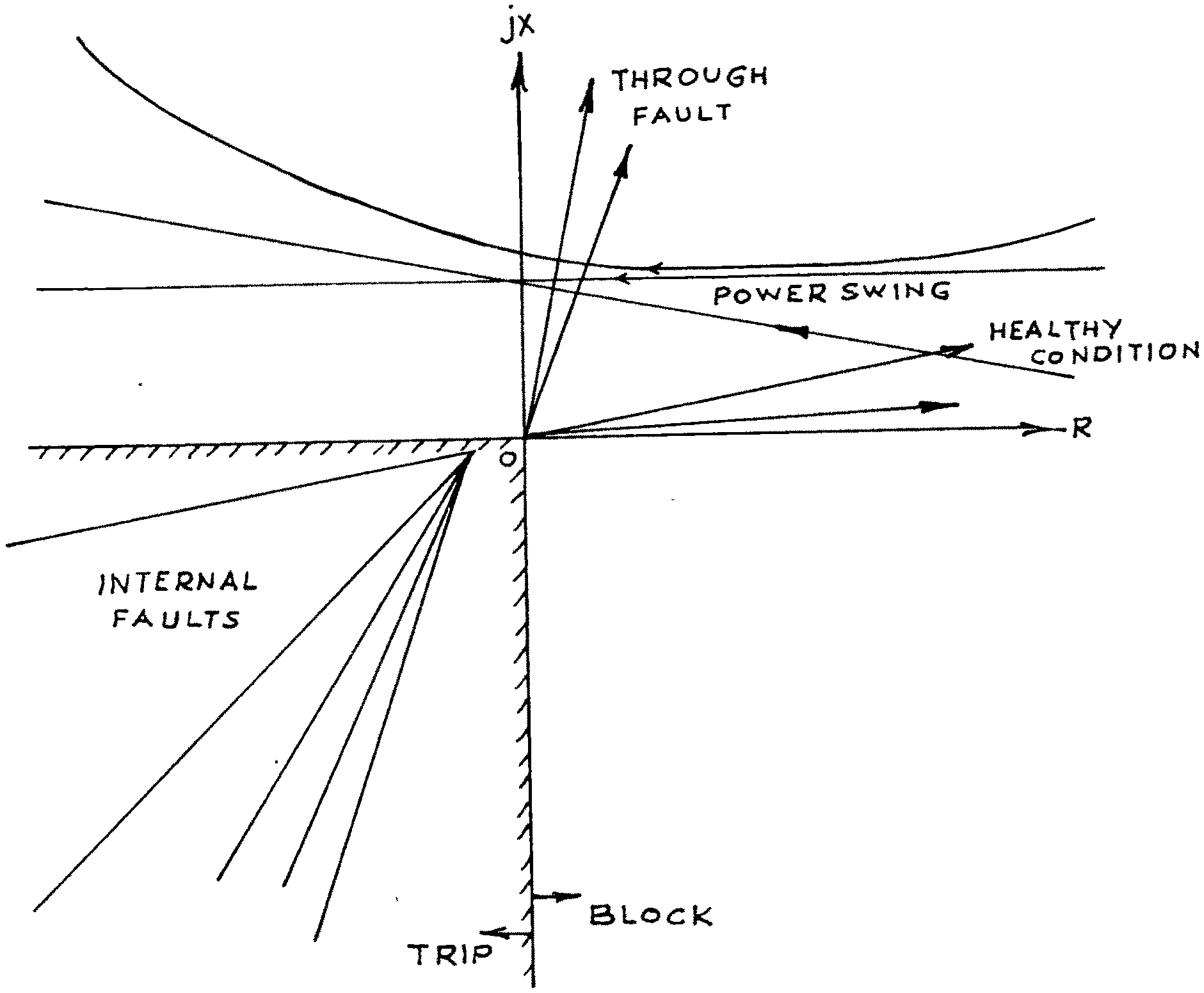


FIG. 9·19 DESIRABLE CHARACTERISTIC

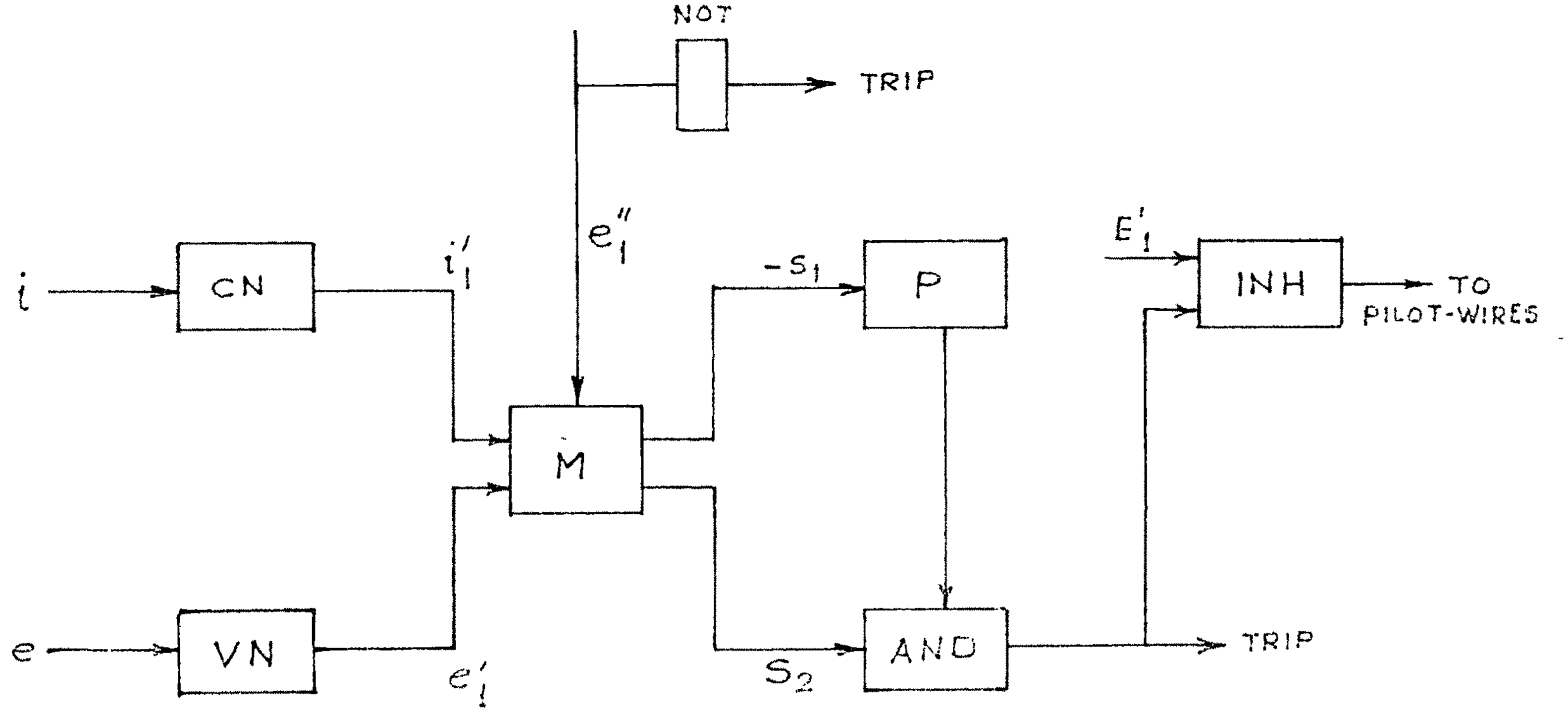


FIG. 9·20 BLOCK-SCHEMATIC DIAGRAM OF THE RELAY is necessary .

Fig.9.21 illustrates the block-schematic diagram of the relay and fig.9.22 illustrates the mode of comparison. Quantities e_1' and $-i_1''$ are applied to the measuring circuits which produce the required signals given by eq.(9.26)for the phase comparison.

$$\left.\begin{aligned} S_1 &= -K_1 i_1'' \\ S_2 &= -K_2 i_1'' \angle 90^\circ \\ S_3 &= -K_3 e_1' \end{aligned}\right\} \quad \text{.... (9.26)}$$

Signals S_1 through S_3 are applied to the positive AND coincidence circuit. The output of the positive AND coincidence circuit is applied to the level detector through an integrator circuit.

The integrator and the level detector are set so that a trip signal is obtained only if the positive coincidence period of the signals S_1,S_2 and S_3 corresponds to the positive coincidence period of S_1 and S_2 only. Since S_1 and S_2 are derived from the current $-i_1''$ either without introducing any phase shift or with the introduction of fixed phase shift, the positive coincidence period of these signals remains a fixed reference period. As illustrated in fig.9.22, a tripping signal is provided only under such conditions when the signal S_3 is positive during the entire

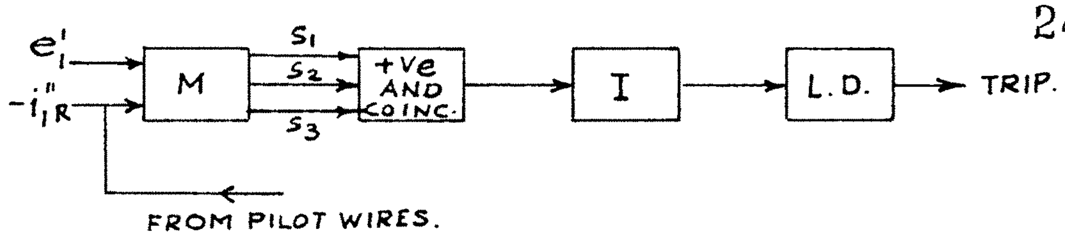


FIG. 9·21 BLOCK SCHEMATIC DIAGRAM

M = MEASURING CIRCUIT. I = INTEGRATOR
L.D. = LEVEL DETECTOR

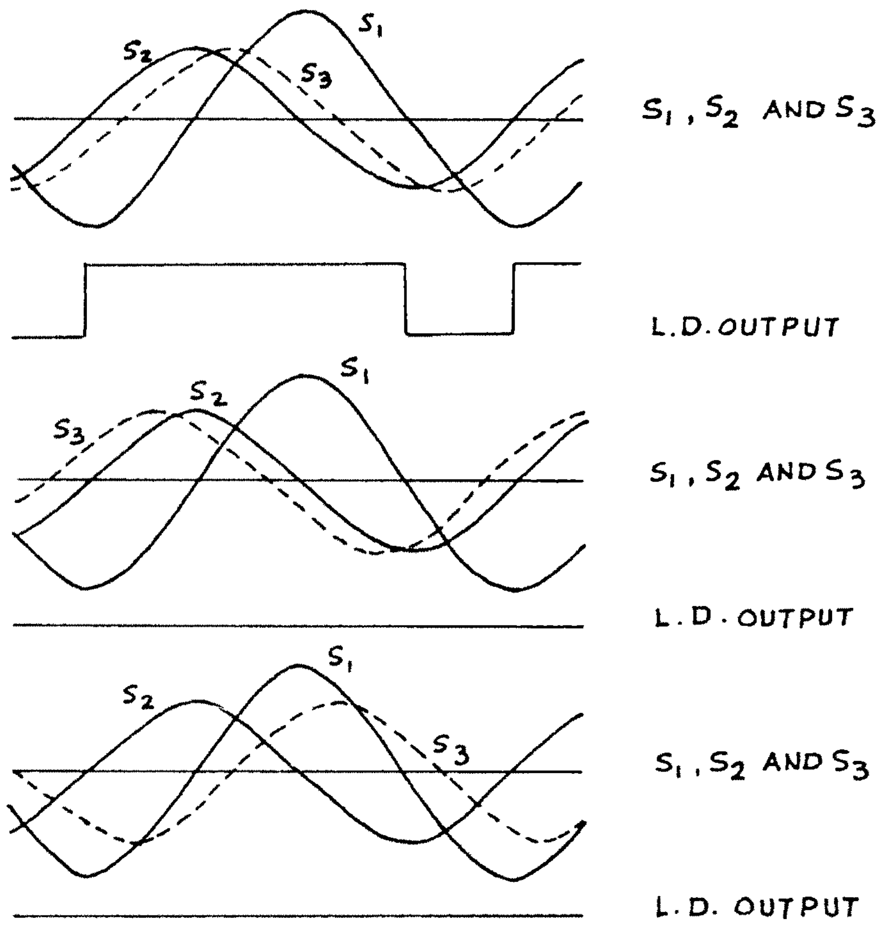


FIG. 9·22 MODE OF COMPARISON

duration of the positive coincidence period of S_1 and S_2, which is the criterion of operation.

9.5 PILOT MONITORING :

In the event of the failure of pilot wires it is necessary for the relaying system to trip the breakers so as to avoid the working of the system without adequate protection being offered. The behaviour of the present relaying schemes during such conditions will now be examined.

9.5.1 Scheme 1 :

In the absence of e_1'' due to the failure of pilot wires the NOT gate of fig.9.20 will issue a tripping signal directly to the breakers. Thus the system will be isolated to avoid its working without adequate protection.

9.5.2 Scheme 2 :

The failure of pilot wires results in the absence of S_1 and S_2 in the phase comparison process (fig.9.21 and 9.22). Signal S_3, acting alone in the positive AND coincidence circuit, provides an input to the integrator a square wave of positive duration of half the cycle. The I and L.D. are set to block the tripping signal only if the input to the integrator is of a duration greater than the positive coincidence of S_1 and S_2. It is clear ,therefore, that the level detector circuit will issue a tripping signal to trip the breakers.