CHAPTER II

SYSTEM REQUIREMENTS AND SHAPING OF POLAR CHARACTERISTICS

2.1 INTRODUCTION :

Developments in multi-input amplitude and phase comparison techniques have made it possible to provide many alternative forms of protection characteristics by suitably arranging the relaying signals. In deciding which of these characteristics most adequately fulfil the requirements of an overall distance protection scheme, proper consideration must be given to the limiting conditions imposed upon the protection by the power system particularly with regard to the realisation of adequate discriminating margins between internal faults on one hand and external faults, power loading, short term overloading and oscillatory systems conditions on the other. The availability of different types of characteristics emphasise the choice between them in different application situations and the considerations forming a basis for choosing the characteristics according to system requirements are analysed in this Chapter.

2.2 POWER SYSTEM REQUIREMENTS :

Since the fundamental principle of distance protection is based on the signals derived at the relaying point at one end of the feeder, an accurate discriminative prediction of conditions adjacent to the remote end of the feeder is not feasible. Hence the choice of optimum settings and the polar characteristics for each of the zones must strike a best overall compromise between many conflicting requirements.

The major requirements of the three zones of distance measurement are summarised below :

2.2.1 Requirements of Zone 1 :

(i) High speed clearance of faults within the protected circuit ideally from both terminations.

(ii) High speed stability against tripping for reverse faults and for faults beyond the remote termination in the direction of the forward reach.

(iii) Restricted reach on either side of the locus of solid faults to discriminate against through load and power swing conditions and against healthy phase impedances.

(iv) Controlled reach in the fourth quadrant of the complex impedance plane to cater for the close-in arcing faults.

2.2.2 Requirements of Zone 2 :

(i) Time graded tripping for faults within the protected circuit and for those in a selected part of the adjacent circuit in the direction of the forward reach so as to cover the remote section of the protected circuit not covered by zone 1 and to provide a partial back-up protection to the circuit immediately following.

(ii) High discrimination for faults behind the relay location and for those beyond the remote terminals of the circuits immediately following.

(iii) Proper discrimination against through load and power swing conditions and against healthy phase impedances.

(iv) Controlled reach to cater for close in arcing faults.

2.2.3 Requirements of Zone 3 :

(i) Time graded tripping for faults within the protected circuit and the whole of the immediately following circuit irrespective of the fault infeeds at the intermediate busbars.

(ii) Directional discrimination may not be essential and normally a controlled reverse reach feature is included to provide slow speed back-up protection to plant immediately behind the relay location.

(iii) Discrimination against power swing, through load and short term overload conditions.

(iv) Controlled reach to cater for close-in arcing faults.

2.3 DISTANCE SCHEMES :

Some typical distance relay characteristics in present day use are illustrated in fig. 2.1 . Fig.2.1(a) is based on the impedance measurement centered at the origin with its radius corresponding to the required impedance setting (plain impedance type). Directional feature and overall control of the reach is provided by a mho type fault detector with a reach setting ensuring the stability of protection under maximum load transfer conditions. Fig.2.1(b) is based on reactance measurements. Fig.2.1(c) is the most commonly used protective scheme with the mho characteristics in zone 1 and zone 2 providing directional control while the zone 3 characteristic is offset to provide remote back up protection for faults immediately behind the relay. Fig.2.1(d) is widely used in continental Europe and comprise of an elliptical fault detector with impedance type zone characteristics and with the facility for offsetting along the real axis of the complex impedance plane. This possesses a restricted reach

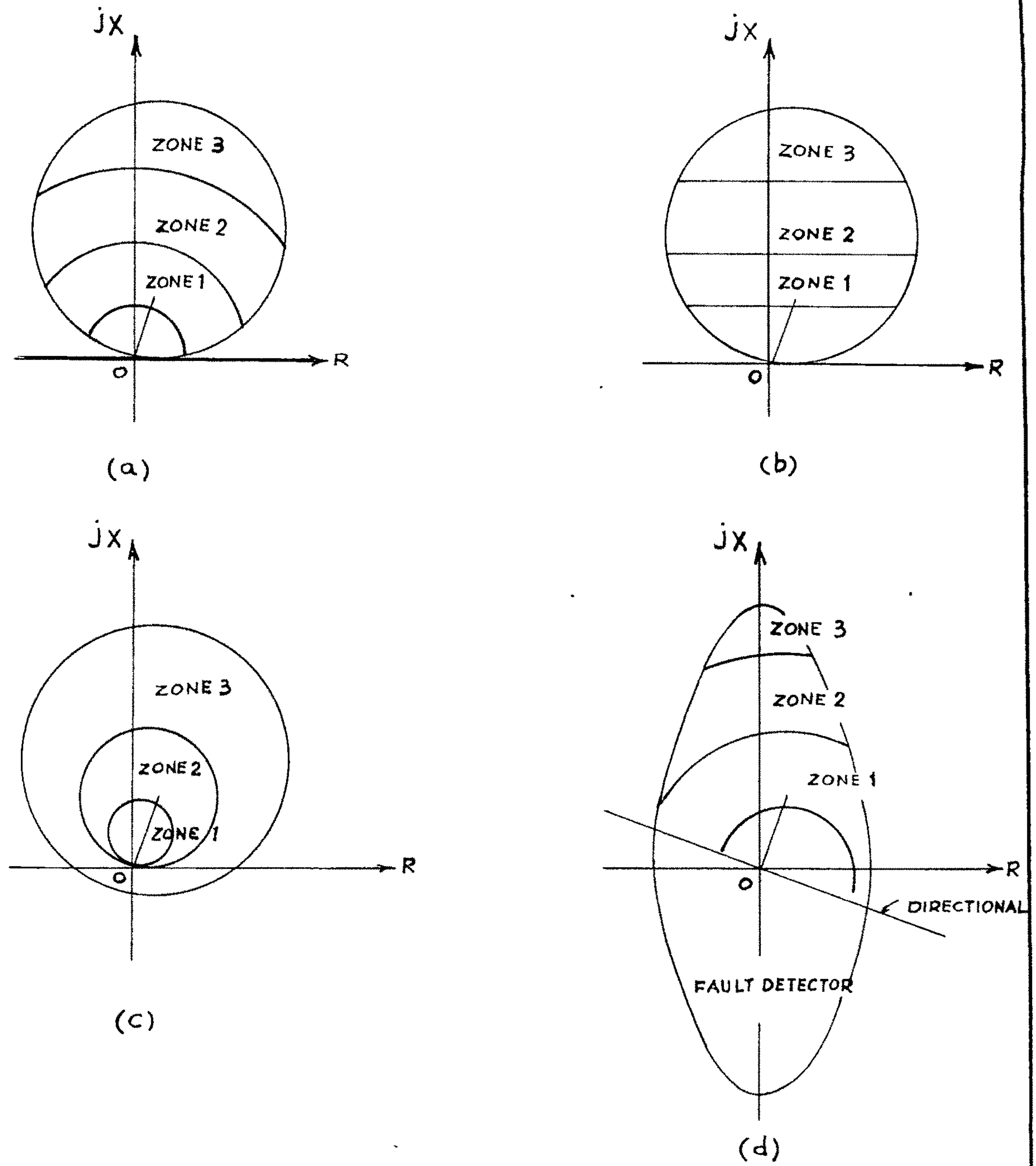
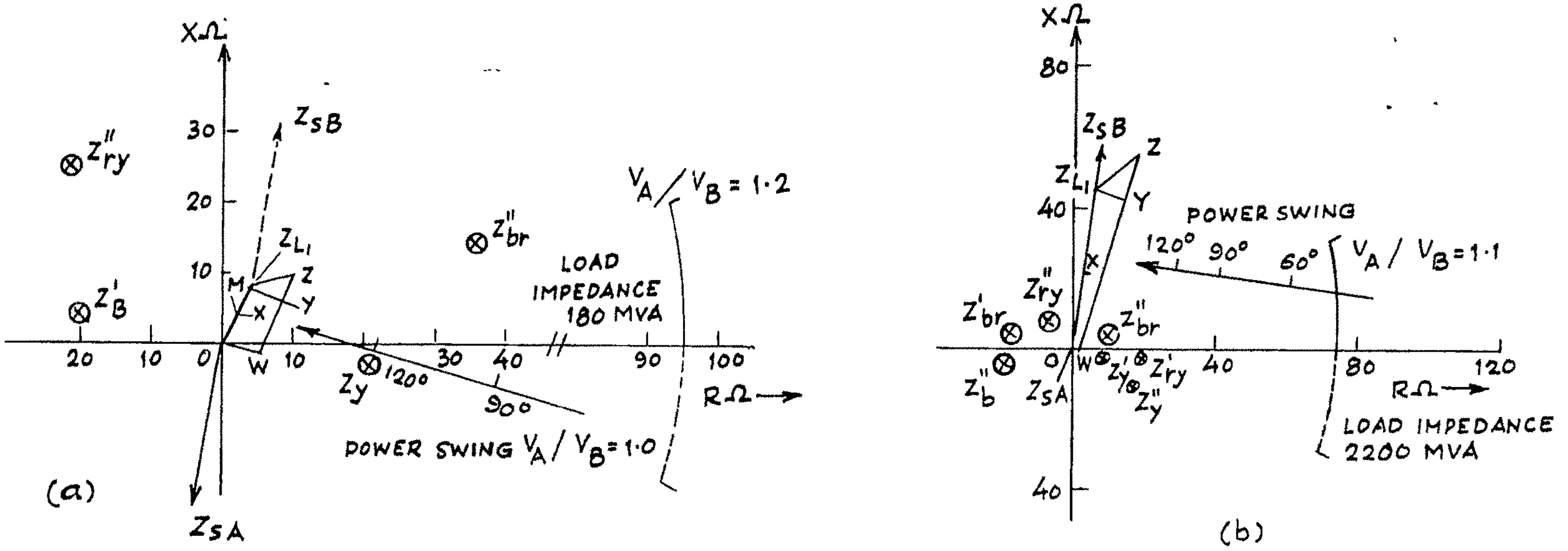


FIG. 2·1 POLAR CHARACTERISTICS FOR MULTIZONE DISTANCE PROTECTION along the real axis which permits high load current transfers while retaining in its measurement the ability to accommodate increased fault resistance values by virtue of the offset impedance characteristic.

In practical distance relay designs ultimately a well defined lower limit of relaying signal exists, below which the comparator will not measure accurately. This limit in terms of power system parameters depend strongly on the ratio of the source to the line impedances and upon the fault location. To cater for a wider range of fault conditions, it is usually the practice to augment the basic measuring signals with additional ones derived from an unfaulted phase or phase pair. In present day distance schemes using sensitive comparator elements, the inherent sensitivity of the measuring elements is high and hence the magnitude of the polarising signal needed is very small. Employing a relatively high level of polarising signal, the tendency of the polarised mho relay characteristic is to elongate and rotate under unbalanced fault conditions, and hence cover higher values of fault resistance as Z_S / Z_L ratio increases. The degree to which this is effective for particular fault conditions and values of fault resistance requires careful analysis.

2.4 FACTORS INFLUENCING THE DISCRIMINATIVE PROPERTIES OF DISTANCE PROTECTION SCHEMES :

The recent studies[23,24,25] conducted to determine the distance protection performance, illustrate the typical areas in the complex impedance plane for which tripping or stability is required [figs.2.2(a) and (b)] . Fig.2.2(a) is for a short 132 kV circuit and fig.2.2(b) is for a 100 mile 400 kV circuit. Marked on the diagram are the impedances measured by the faulted phase relays and the impedances measured by the healthy phase relays. Typical loading and power swing conditions are also illustrated. It is seen from the diagram that close control of protection characteristic may be required to provide discrimination between those conditions which require tripping and those which do not. The protection characteristics shown in fig.2.1 provide a measure of discrimination. This can be further improved by the selection of the most appropriate characteristic to fulfil particular system requirements. It is apparent that under internal fault conditions the protection characteristic shape for the 132 kV circuit tends to be most significantly influenced by the effects of fault resistance. For the long 400 kV line stability against load and power swing conditions are more important in determining the protection characteristic shape.



<u>10 MILE 132 kV CIRCUIT</u>

$Z_{S_1}/Z_{L_1} = 15\cdot0$ MAXIMUM LOAD = 800 A (180 MVA)

$Z_{L_1} = 6\cdot5$, $Z_{SA_1} = Z_{SB_1} = 18\%$ (550 MVA)

<u>100 MILE 400 kV LINE</u>

$Z_{S_1}/Z_{L_1} = 0\cdot2$ MAXIMUM LOAD = 3200 A (2200 MVA)

$Z_{L_1} = 4\cdot5$, $Z_{SA_1} = Z_{SB_1} = 6\%$ (16·6 GVA)

<u>IMPEDANCES MEASURED BY HEALTHY PHASE RELAYS.</u>

Z''_{br} , Z''_{ry} : IMPEDANCES SEEN BY PHASE FAULT RELAYS FOR CLOSE UP r-e FAULT.

Z'_{y}, Z'_{b} : IMPEPEDANCES SEEN BY EARTH FALTH RELAYS FOR CLOSE UP y-b FAULT.

Z'_{ry}, Z'_{yb} : IMPEDANCES SEEN BY PHASE FAULT RELAYS FOR CLOSE UP y-b FAULT.

Z''_{y} , Z''_{b} : IMPEDANCES SEEN BY EARTH FAULT RELAYS FOR CLOSE UP r-e FAULT.

FIG. 2·2

DISTANCE PROTECTION PERFOMANCE DIAGRAMS

<u>IMPEDANCES MEASURED BY FAULTED PHASE RELAY:</u>

OZ_{L_1} = SOLID FAULT AT END OF PROTECTED LINE.

OM = SOLID FAULT AT MID POINT OF PROTECTED LINE.

OX = 2 ohm RESISTIVE FAULT AT MID POINT OF PROTECTED LINE WITH ZERO LOAD TRANSFER.

OY = 2 ohm RESISTIVE FAULT AT END OF PROTECTED LINE WITH MAXIMUM LOAD TRANSFER OUT OF RELAYING END.

OZ = 2 ohm RESISTIVE FAULT AT END OF PROTECTED LINE WITH MAXIMUM LOAD TRANSFER INTO RELAYING END.

OW = 2 ohm RESISTIVE FAULT AT RELAYING POINT WITH MAXIMUM LOAD TRANSFER OUT OF RELAYING END.

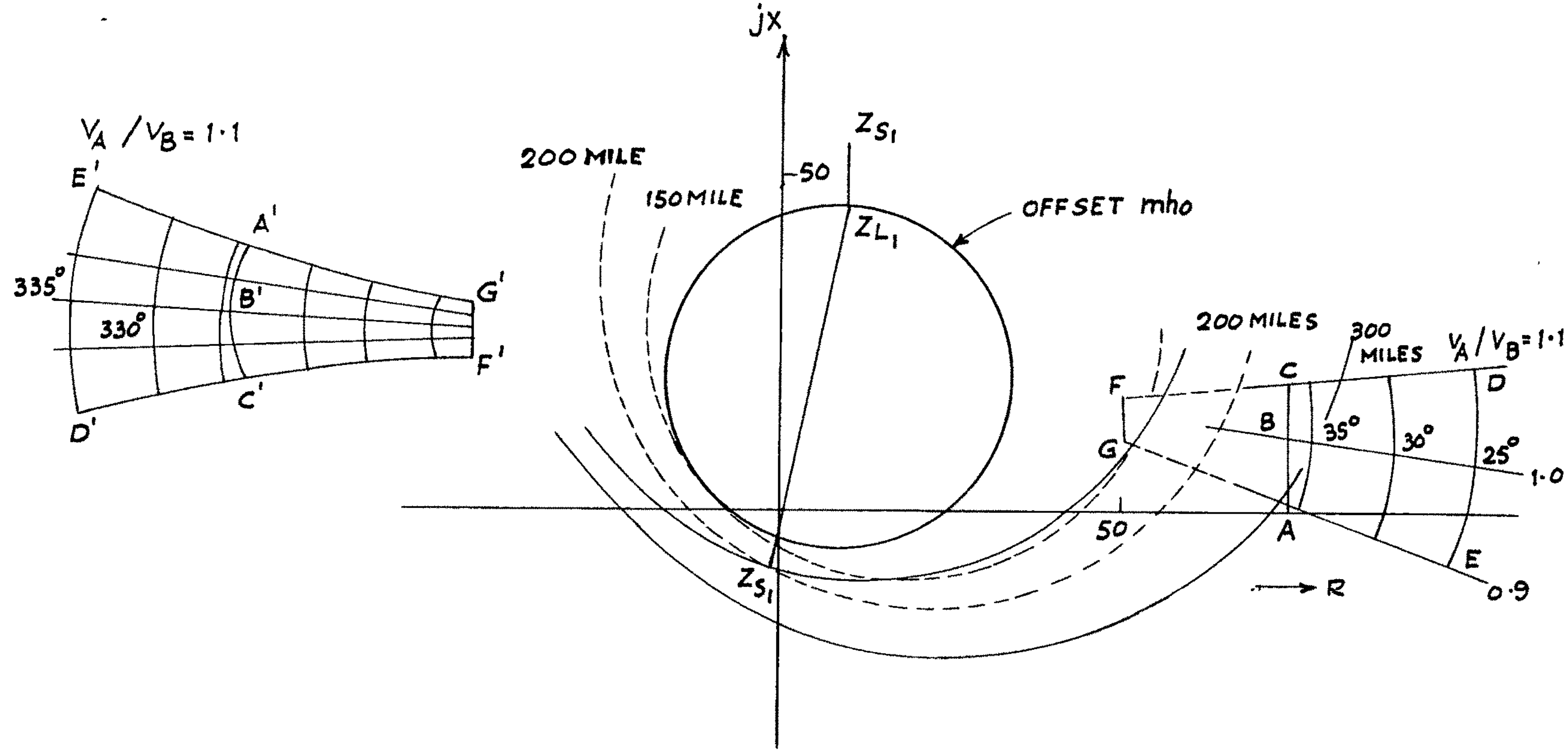
2.5 DISCRIMINATION AGAINST MAXIMUM CIRCUIT LOADING CONDITIONS :

The growing demand for electricity and the economics associated with its supply at low rates to consumers has resulted in the construction of large capacity generating stations at suitable locations. Large load centres are often located at great distances from such generating stations. Bulk power is carried from these stations to the load centres over EHV transmission lines for which voltages upto 765 kV have been used. Present trends forecast that voltages upto 1200 kV a.c. may be used as transmission voltages by the end of the present decade. These conditions are particularly true for vast countries like USA, USSR and India. The reliability and security of the EHV line/Inter-tie is a very important factor and these lines impose most severe practical conditions. The protection characteristic must exclude impedance values corresponding to maximum healthy circuit loading conditions and short-term over loading conditions.

Latest developments in large capacity generating machines and their associated accessories (static excitation schemes and electronic governors) has resulted in the operation of the system at or near its steady state stability limit. This particular operating mode necessitates a clear and closer discrimination against power swings, maximum healthy circuit loading and short- term overloading conditions.

Fig.2.3 illustrates the load impedance characteristics of a 100 mile 400 kV circuit, with the characteristic of a mho relay with 10 percent offset, superimposed. The load impedances may take any value within these limits. The curvilinears ABCDE and A' B' C' D' E' refer to the sending and the receiving end conditions respectively for a load transfer of 2200 MVA, and they are extended to FG and F'G' to show the maximum short term loading condition (about 20 minutes).

For the condition where the relay characteristic angle corresponds to that of the protected line, encroachments in the overload impedance area will occur when the forward reach setting approximates 200 miles. If, as is usually the case, the relay characteristic angle is offset, more pronounced encroachments are encountered (broken lines). It is clear that the conventional offset mho characteristic will introduce constraints in permissible circuit loading and that the present practice of advancing the relay characteristic angle worsens the situation. With this limitation the degree of remote back-up protection provided by the conventional protection characteristic is barely sufficient.



MAXIMUM LOAD = 2200 MVA, Z = 72·5 ohms,

OVERLOAD = 2800 MVA, Z = 57 ohms.

Z_{L_1} = 47 ohms.

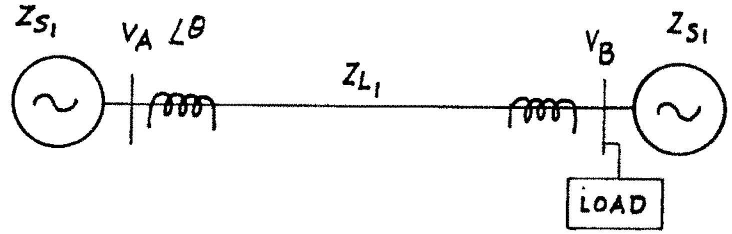


FIG. 2·3 LOAD IMPEDANCE AREAS-100 MILE 400 kV LINE WITH MHO RELAY WITH 10% OFFSET SUPERIMPOSED

Also the apparent impedance values represented refer to maximum circuit loading conditions and an additional margin over and above these levels may be required to cover system conditions following extensive circuit tripping, where for very short periods a higher circuit loading may be obtained. Hence it is clear that in many circumstances suitable shaping of zone-3 characteristic will be required so as to provide a restricted and controllable reach along the resistive axis of measured impedance.

2.6 POWER SWING REQUIREMENTS :

The effect of wider deviations in angle between busbar voltages is to present to the distance relays an apparent impedance which will encroach further on the protection characteristics. For zones 2 and 3 tripping will occur if the apparent impedance falls within the characteristic for longer than the corresponding zone-time settings and tripping will occur in zone-1 characteristic if the apparent impedance falls within the characteristic for longer than the zone 1 comparison time. Whether this occurs or not depends upon the location of the electrical centre of the system with respect to the relaying point. Fig.2.4 illustrates the locus of power swing impedances for a typical 2000 MW generating station connected to the system via one or four 100 mile 400 kV circuits. It is seen that

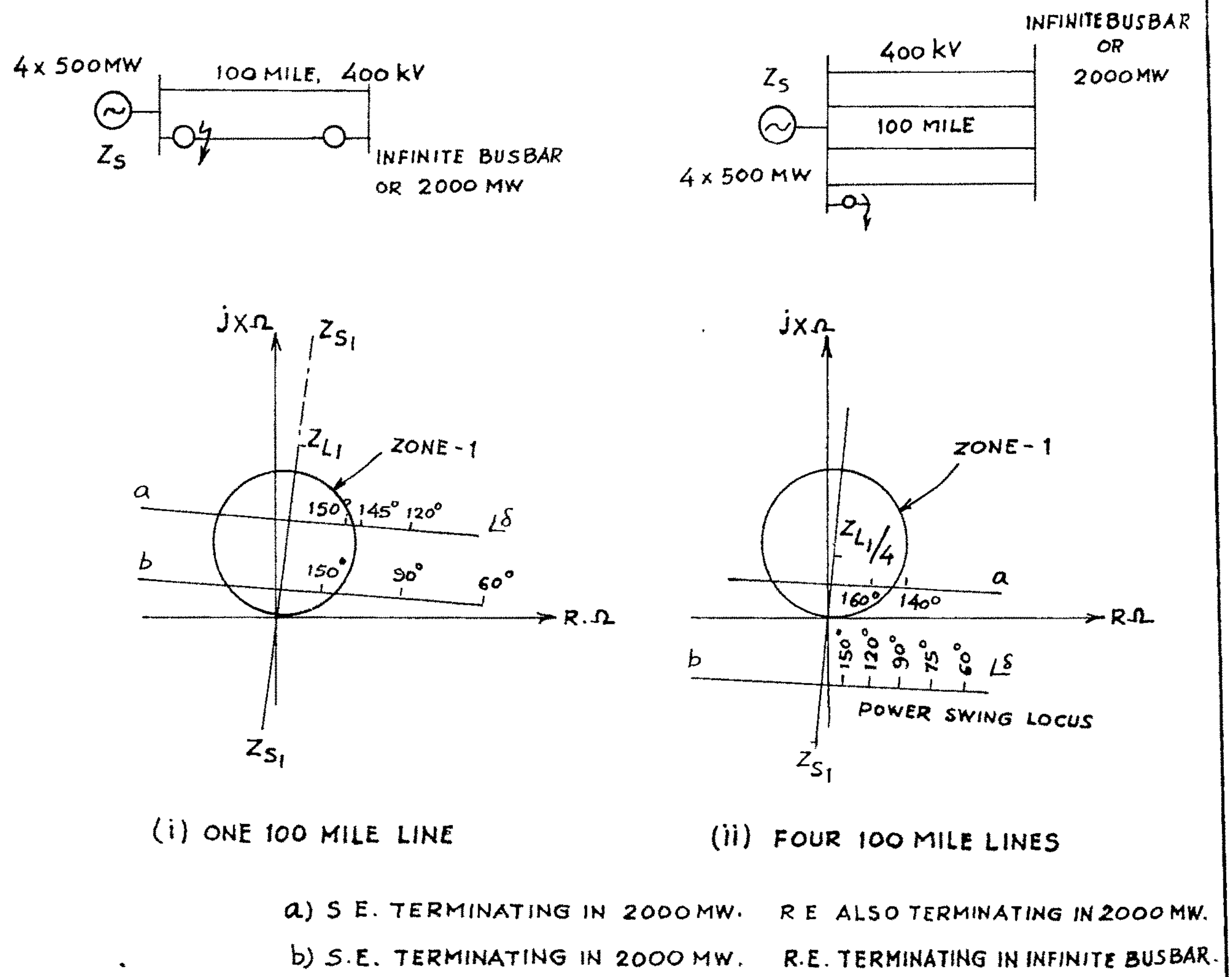
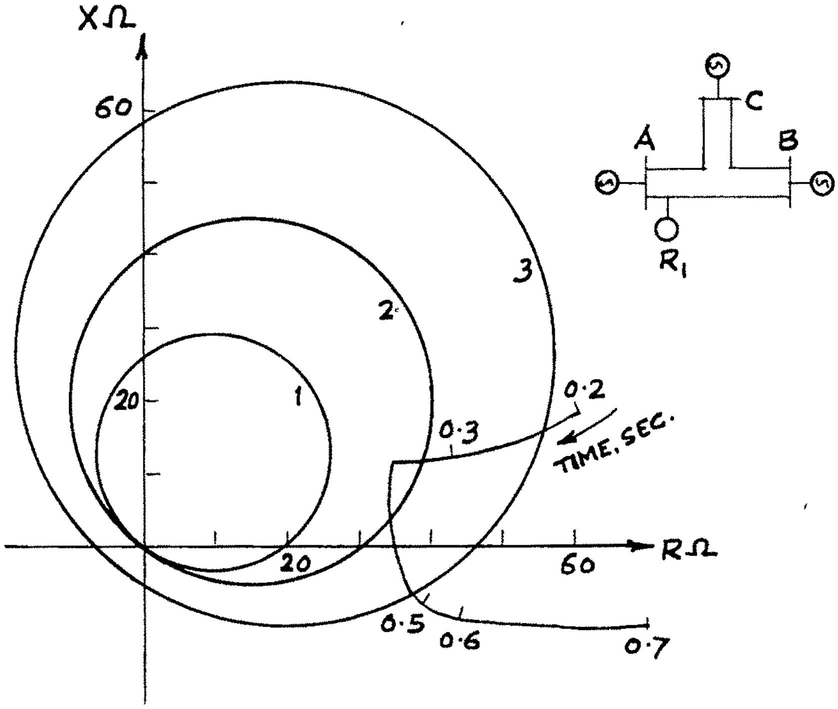


FIG. 2·4 SIMPLIFIED POWER SWING LOCI FOR 2000MW GENERATING STATION locus of first swing, may or may not traverse the relay zone-1 characteristic, depending upon system impedance levels. Fig.2.5 illustrates the impedance loci for a more complex system condition. When one complete slip cycle is lost, distance protection tripping will occur in all cases where the electrical centre of the system is contained within the zone 1 protection characteristic and shaping of the characteristic cannot influence this. In situations where one or two slip cycles may be lost, but for which resynchronisation would ultimately take place owing to voltage regulator and governor action, the ultimate recovery of the system may be prejudiced by the undesired tripping of the interconnector.

2.7 DISTANCE PROTECTION SCHEME REQUIREMENTS :

The essential requirement in choosing the characteristics of distance protection is that of closely matching their shapes to the expected fault areas on the impedance plane in which the protection should operate. The polar characteristic for zone-1 is required to discriminate between internal fault conditions and external fault conditions. The choice of the polar characteristic is influenced by the X/R ratio of the fault loop. Arcing faults close to the relay location can impose particular difficulties. It is here that the type and level of polarisation can contribute beneficially to the distance protection performance.



AB = AC = BC = 100 MILES, 400 kV

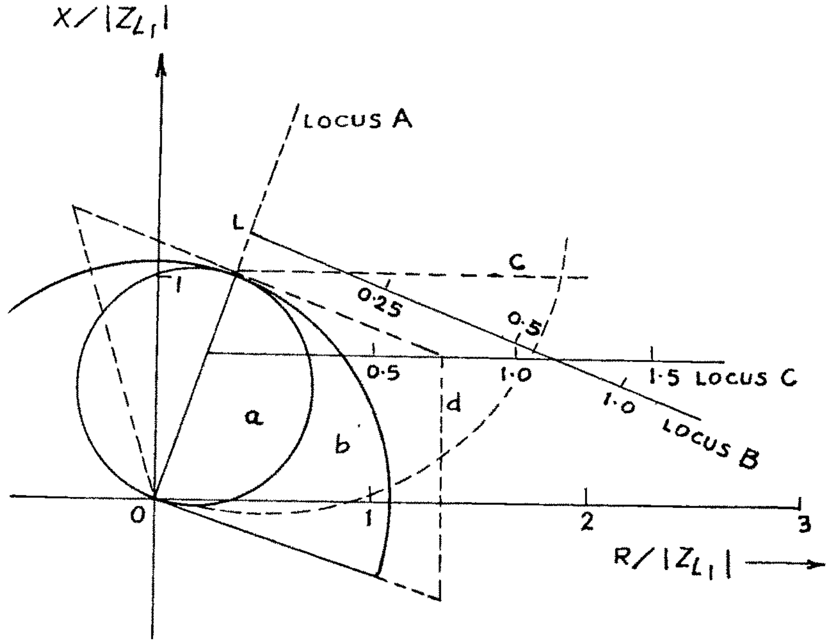
GENERATING CAPACITY AT A & B = 2000 MW

INFINITE BUSBAR AT C

3 PHASE TO EARTH FAULT AT A CLEARED IN 0·14 SEC.

FIG. 2·5 APPARENT IMPEDANCE LOCI UNDER OSCILLATORY CONDITIONS

It is of course necessary to evaluate both the apparent impedance presented to the protection and the effective protection characteristic for the same primary system conditions and then only a reliable estimation of the coverage of protection can be made. Fig.2.6 presents a comparison of performance of different protection characteristics now in use for zone-1. The characteristics shown are a mho characteristic with low level of polarisation, a plain impedance characteristic with directional control, a reactance characteristic with 'mho' control and a quadrilateral characteristic synthesised to give maximum discriminating margins. The mho characteristic permits a maximum value of R_F for a mid point fault and which reduces for faults close up to the relay location given by the intercept of the characteristic on the R-axis. If the infeeding conditions at the two ends of the circuits are such that the locus of close up faults has a negative slope, then the coverage further reduces and becomes zero when the locus is tangential to the mho characteristic. The plain impedance characteristic with directional control offers a higher value of R_F for mid point fault and still higher values for close-up faults. The reactance characteristic, which is widely used for earth fault protection, may be arranged to give the greatest coverage in the resistance axis, but where the characteristic is parallel to the resistance axis, it has a tendency to



LOCUS A : IMPEDANCE LOCUS FOR SOLID FAULTS.

LOCUS B : IMPEDANCE LOCUS FOR FAULT AT 0·95 Z_{L_1} WITH MAXIMUM POWER TRANSFER AT RELAYING POINT.

LOCUS C : IMPEDANCE LOCUS FOR MID POINT FAULT WITH ZERO POWER TRANSFER.

a. Mho CHARACTERISTIC

b. IMPEDANCE CHARACTERISTIC

c. REACTANCE CHARACTERISTIC

d. SHAPED CHARACTERISTIC

FIG. 2·6 RELATIVE PERFORMANCE OF PROTECTION CHARACTERISTICS IN PRESENCE OF ARC RESISTANCE overreach at low fault resistances. The quadrilateral characteristic provides a close match to the probable fault area and also has sufficient reach in the resistance axis.

As regards the range of fault resistance values likely to be encountered in practice, the limiting values of arcing fault resistance may be evaluated using Warrington's formula for a wide range of system conditions. The highest fault resistances are encountered where the fault current is low. For example, for a 10 mile 132 kV line with $Z_s/Z_n = 7.0$ corresponding to source infeed of 350 MVA, the fault resistance comes to about 0.5 ohm, while, a 100 mile 400 kV line with practical limit of $Z_s/Z_n = 1.0$ corresponding to a fault infeed of 3500 MVA gives a fault resistance of only 0.45 ohm.

Summarising, for zone-1, the limiting conditions of application are governed mainly by resistive faults close to the relaying point. The use of an additional polarising signal in the polarised mho relay provides an extended reach in the resistance axis, and successfully overcomes this condition and can be regarded as a competitor to the shaped characteristics for zone-1. However, in circumstances where it is desirable to reduce the width of the polar characteristics to improve discrimination against power swings or healthy phase encroachments as in the case of encroachments under heavy loading are reduced if the established offset impedance form of characteristic is retained. The shaped polar characteristics allow a long forward reach without correspondingly reducing the discriminating properties in the load regions. The use of these characteristics reduces the danger of an incorrect trip under power swing conditions in cases where during fault recovery, the apparent circuit impedances may be continuously depressed for periods sufficiently long to initiate tripping in 3rd zone. The quadrilateral characteristic with independent reach adjustments in the reactance and resistance axes provides a flexible back up characteristic.

2.8 APPLICATION TO PROTECTION OF COMPENSATED LINES :

As series compensation is now normally adopted for almost all long EHV lines for improving the stability of the systems, the reliability and security of the system becomes a very important factor. One of the major problems faced with the application of series compensation is the protection of transmission systems under fault conditions. This problem is further accentuated by the location of the series capacitor which is governed by other considerations such as improvement of stability, self excitation of machines and power frequency over voltages.

Conventional distance as well as directional comparison schemes require that the capacitor protective gaps flashover faster than the operation of the relay and this factor however depends on the availability of sufficient fault current for all locations of the fault. In view of these difficulties phase comparison carrier schemes are better suited for the protection of compensated lines. The factors to be taken into account while resorting to this method are :

(1) Attenuation along the line which governs the signal to noise ratio in the receiver.

(2) Tripping and stabilising angles: The choice of tripping and stabilising angles is somewhat difficult because the phase angle differences between the currents at the two ends of the line may vary considerably on internal faults, particularly if we take account of difficult conditions and complex faults such as broken conductors or multiple grounds. It is necessary that the tripping angle be as large as possible to cover these. The phase angle requirements are normally approached from the stabilising condition which is more specific.

(3) Fault settings related to the capacitance current.

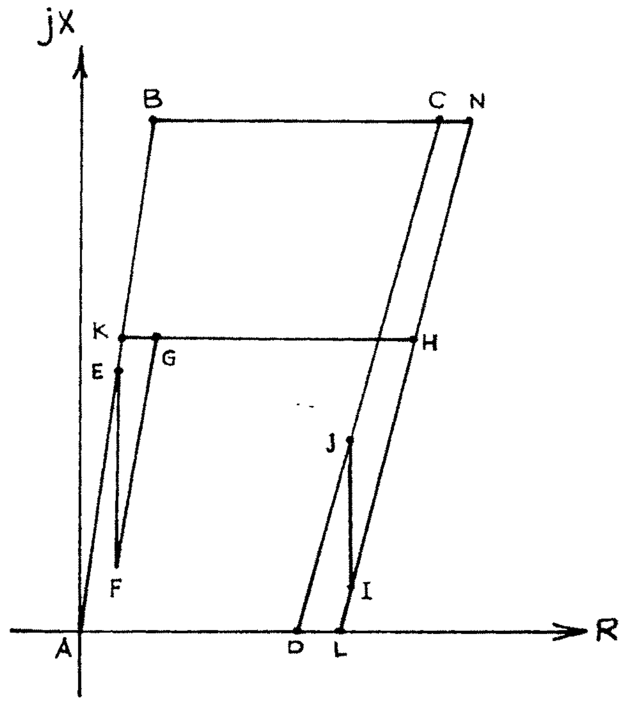
(4) Stability under reset conditions, and

(5) Reasonable performance of the current transformers under transient conditions.

In series compensated lines, it is desirable to monitor the phase comparison schemes with distance relays having quadrilateral characteristics rather than with overcurrent relays. The major advantage of such a characteristic is its low susceptability to overloads, its inherent out of step blocking feature, and it also performs equally well irrespective of whether the capacitor protective gaps flash over or not.

2.8.1 Directional Distance Relay for Compensated Lines :

The use of directional distance relays present many problems on a compensated line such as wrong indication to the directional element, circulating current due to unsymmetrical gap operation and shifting of line impedances as the series capacitors cut in and out. Of these three,the first problem poses a serious threat to the use of distance relaying. However, if the series capacitor banks are positioned at the center of the protected zone, the correct operation of the distance relay is ensured if the capacitor reactance is less than 50 percent of the line reactance. If this limit is exceeded an internal fault will appear as an external fault for the relay and vice versa. Fig.2.7(a) shows the probable fault areas of a compensated and uncompensated transmission line on an impedance plane. Any relay with the pick up characteristic AKHL is well suited for the protection of such a transmission system. The

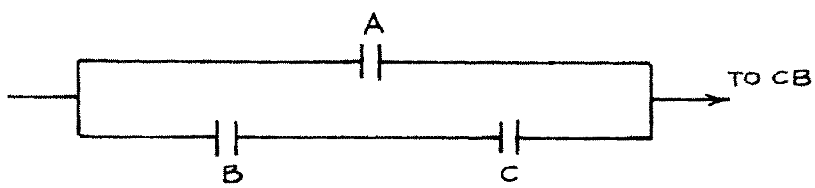


(a) PROBABLE FAULT AREAS OF LINES

ABCD - UNCOMPENSATED LINE

AEFGHIJD - SERIES COMPENSATED LINE

AKHL - CHARACTERISTICS SUITED FOR PROTECTION OF COMPENSATED LINE



(b) SCHEMATIC DIAGRAM OF TRIP CIRCUIT CONTACTS

A - CONTROLLED BY RELAY AKHL

B - CONTROLLED BY RELAY ABNL

C - CONTROLLED BY A SIGNAL FROM THE GAP CIRCUIT OF THE SERIES CAPACITOR

FIG. 2·7 FAULT AREA AND SCHEMATIC DIAGRAM OF CONTACTS protective system should discriminate and function properly immaterial of whether the capacitor gap flashes over or not. This can be realised by employing two comparators yielding the pick up characteristics ABNL and AKHL. The trip signal given by the relay AKHL can be used when the series capacitor gap does not flash over. The relay ABNL comes into operation only when the gap flashes over. For this a signal derived from the gap circuit of the capacitor is 'AND' gated with the output of the relay ABCD. A schematic of the arrangement of contacts is as shown in Fig.2.7(b). It should be however noted that in such schemes only the circuit breakers at the sending and receiving ends operate for faults anywhere in the protected zone.

2.8.2 <u>Distance Relay Monitored Phase Comparison Schemes</u> :

This scheme compares the phase of the currents at the two ends of the transmission line through a carrier and provides a trip signal only when the currents are of fault magnitude and are corresponding to the tripping angle. The arrangement of the tripping and blocking characteristics required for phase comparison monitoring is shown in fig.2.8. Two relays are used per phase and each of them is provided with a quadrilateral pick up characteristic. One is a blocking unit MB and the other is a tripping unit MT. The reach of the relay MB is greater than that of MT and is so adjusted that for a fault near station B, the impedance locus falls within the characteristic of MT relay at

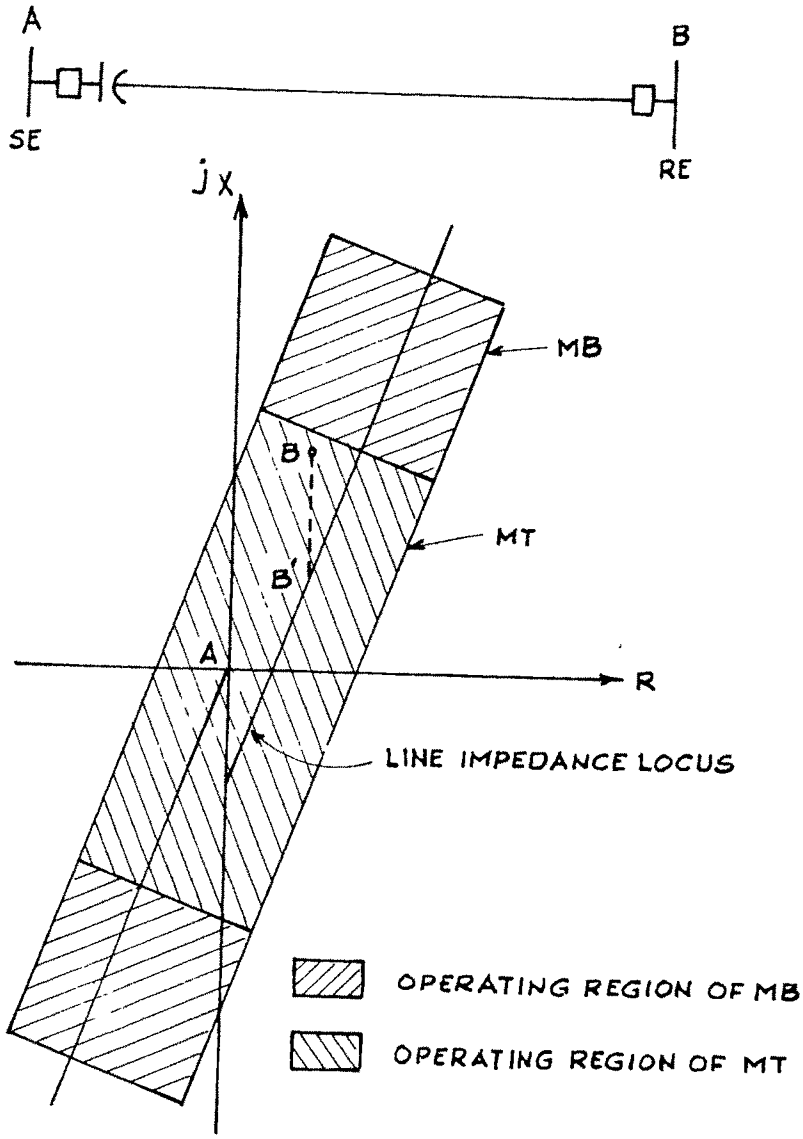


FIG. 2·8 QUADRILATERAL POLAR CHARACTERISTIC FOR TRIPPING AND BLOCKING RELAYS station A, immaterial of whether the capacitor gap flashes over or not. During a fault, MB relays produce an output which initiates the phase comparison. If the phase comparison scheme decides that the fault is internal and if the MT units also operate a tripping signal is produced.

The subsequent chapters of the present work deal with the developments in multi-input phase and hybrid comparison techniques in providing the protective arrangements.