CHAPTER I

INTRODUCTION

Over the past several years there has been widespread interest in extra high voltage transmission systems. There are obvious economic advantages to be realised through the use of EHV in system interconnections, power pooling and in the installation of high capacity unit generators. The EHV system capable of transmitting large blocks of power thus becomes an extremely important part of the power systems. The increased use of longer and more heavily loaded transmission lines and the demand for greater reliability of service and economical switching arrangements utilising minimum number of circuit breakers call for significant improvements in protective relaying schemes.

Power system protection can be regarded as an insurance against fault damage and the amount of insurance which is taken out depends upon the degree of risk involved. In modern interconnected extra high voltage power systems the risk involved in not providing fast and reliable protection to clear faults is very high indeed. Shorter operating times have become more essential to preserve dynamic stability as the character and loading of the system approaches design limits. Further, high speed clearing of faults offers a significant economic contribution to the power system. Studies have shown that a given system can transmit larger amounts of power without loss of synchronism when faults are cleared in shorter times. Faster clearing of faults also reduces line conductor damage. Burned or pitted conductors are more subject to failure due to corrosion and they also result in objectionable corona and radio noise levels particularly at higher voltages.

To meet the requirements of better protective relay performance, a gradual improvement in the design of conventional electromechanical relays has taken place over the years, but there is a limit to the sensitivity which can be achieved on electromechanical relays without sacrificing reliability. Stability against shock and vibration is particularly difficult to achieve on the more sensitive units with low operating torques. The use of static relays has made it possible to achieve greater sensitivity and at the same time obtain excellent mechanical stability.

From both the manufacturer's and user's view point, static relaying permits rationalisation of basic elements designed to meet the various protection requirements, a feature which has always been difficult to achieve with the electromechanical relays. Moving coil, induction cup, and attracted armature relays have had some success, but flexibility has always been restricted.

The use of semiconductor devices for obtaining the various protective functions provide the answer for high speed relaying. Whereas electromechanical relays are limited in their operating time by the inherent inertia of the system, static relays can operate theoretically instantaneously due to the absence of any moving contacts. Yet another salient feature characterising the static relays is that the operating time of some static relays can be made independent of the fault location but a function of the instant on the voltage cycle at which the fault occurs. This is not the case with electromechanical relays which produce torques as a function of the magnitude of the input quantities.

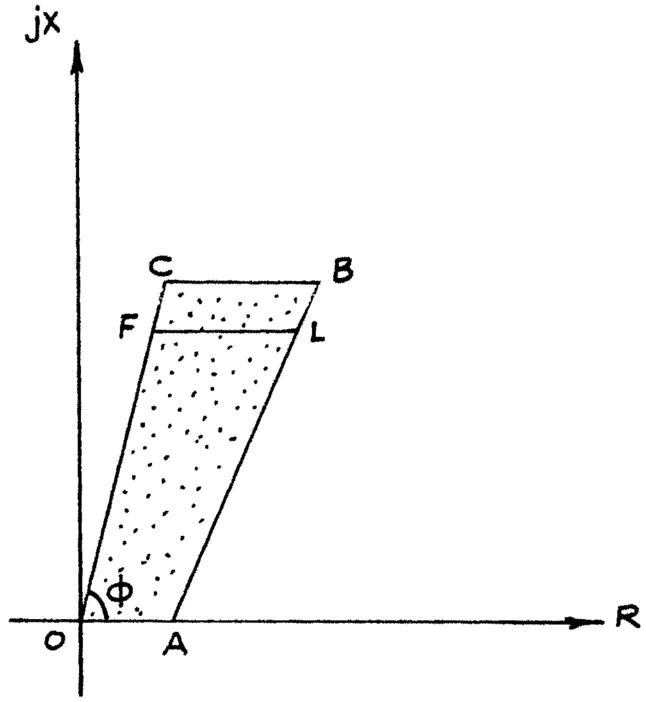
There are many more advantages to be gained by using semiconductor relays. Absence of moving contacts implies less maintenance problems. Furthermore the burden on the protective current transformers and potential transformers are also well below those obtained with electromechanical relays. Needless to say that static relays occupy lesser floor area of the control room when compared to their electromechanical counterparts.

Perhaps the greatest advantage provided by these static units is the flexibility of the pick-up characteristics which these units permit. The control of the inverse characteristics of time overcurrent units or a variety of pick-up characteristics of distance units are just two examples of this feature of static devices. Electromechanical relays provide only circular or straight line characteristics on the impedance plane and any modification of these require connecting the contacts of various relays in series which is not desirable. The use of semi-conductor devices have resulted in new concepts of relaying by means of which special characteristics are possible without resorting to the series connection of contacts.

The development of extra high voltage lines has necessitated rethinking as regards the characteristics required for the distance units for protecting these lines. Arising from the more and more complicated structure of high voltage networks and in particular intensive linkage it happens more and more frequently that existing distance relays cause increasing incorrect operations. The only method of overcoming these errors without complicating the protective system is to use a very strict tripping area.

In particular, in case of distance relays, the tripping area represented on the R-X diagram should strictly envelope the overall assembly of the operating points of the defective line.

On an R-X diagram the characteristic of a line is represented by a straight line (fig.1.1), the length of which is proportional to the length of the line under consideration. It is the locus of the operating points of the line subjected to metallic faults. To this locus, inclined at an angle ϕ to the resistance axis, is added the total fault resistance to give the area of fault probability in the impedance plane. For any fault say at F, the vector LF is due to the resistance component of the fault comprised of the arc resistance and eventually the earthing resistances of the equipments and the neutral of the transformers in case of a single phase fault. The fault resistance increases somewhat for faults towards the remote end of the section because less of the total fault current flows through the relay even though the actual fault resistance may be reduced by the extra current fed in from the remote end. The length of the protected circuit, and the fault resistance appropriate to the line construction determine the area of fault probability in the impedance plane in a particular case, along with the fault infeeds



(a) AREA OF FAULT PROBABILITY ON IMPEDANCE PLANE

(b) SYSTEM UNDER CONSIDERATION

FIG. 1·1 FAULT AREA ON COMPLEX IMPEDANCE PLANE immediately behind the relay location and at the remote termination of the circuit. The quadrilateral characteristic hence suggests itself as a general characteristic and as being potentially capable of meeting different and specific requirements as they arise. Ideally the reach settings of the characteristic in the resistance and reactance axes should be independent as should be the slopes of the constituent sides, for it to cope with the range of conditions encountered in ordinary practice. This is further confirmed by a reference to report on the desirable shapes of distance relay characteristics by J. Landmark Braten[1] and J.W. Hodgkiss[2]. This report points out the desirable features in the distance relay characteristics as follows:

1) The characteristic should cover the impedances in question with some margin because the impedance of the circuit cannot be stated exactly.
2) The characteristic should as far as possible ensure satisfactory operation in the presence of
   a) Additional Resistance in arcs, tower footings etc. measured in some cases as impedance with important reactive components ;
   b) Small load impedances - even if of the same order of magnitude as the fault impedance ;
   c) Power swings ;
   d) Infeed of currents not measured by the relay in question but through teed feeders within the

protected area or through other unfaulted lines in case of back up.

The distance relay characteristic, depending on the nature of the fault and or on the other conditions in the network, should have desirable shapes for all such conditions which can occur when the relay in question is called upon to operate.

The desirable shapes for the distance relay characteristics are shown in fig.1.2[1,2] . The characteristic should be directional and should not operate in the forward direction for faults in the 3rd quadrant. The characteristic should enter the second and fourth quadrant at an angle (compared with R axis) taking into account selectivity, dynamic properties and angular errors. The limitation to the right (on R axis) is determined by the maximum resistance to be measured. In some other cases limited extension may be necessary to avoid unwanted tripping in case of power swings. Some extension in the fourth quadrant is necessary in cases when single phase tripping is wanted and a relay in the unfaulted lagging phase measures a small impedance in the fourth quadrant due to heavy load.

The above considerations lead to desirable shapes of the distance relay characteristics similar to those in

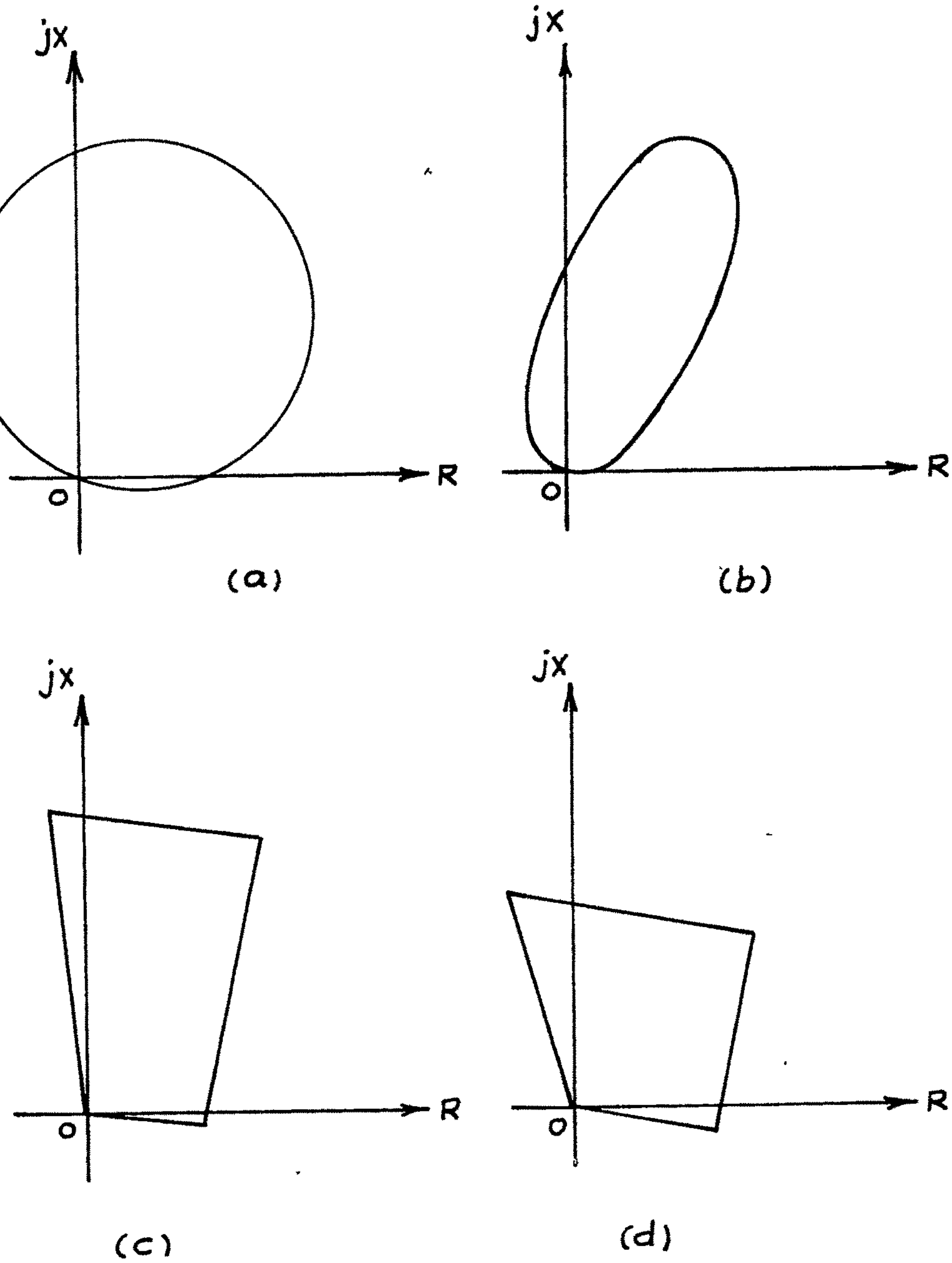


FIG. 1·2 DESIRABLE SHAPES OF CHARACTERISTICS fig. 1.2 . A free choice of the slopes of the constituent sides and the extension to the right are desirable. Most of the development in the field of distance relaying has been towards achieving this end with the simplest arrangements.

The proposals for electronic relays are not new and references relating to their application to power system protection may be found in the literature of 1928 onwards. In that year Fitzgerald published a paper describing a scheme of electronic pilot system for the protection of long lines[3]. This scheme was subsequently discarded because of the high cost and the lack of reliability of the valves available at that time. In 1934 Wideröe described a series of electronic circuits for most of the common types of protective relays[4] and later Loving developed circuits for many common functions pertaining to protective gear[5]. Macpherson, Warrington, and McConnell gave information about an electronic 'mho' relay in 1948[6], and subsequently Barns and Macpherson confirmed the efficiency of this method by their field experience[7]. Satisfactory field experience on fast carrier scheme was subsequently reported by Barns and Kennedy in 1954[8]. Bräten and Hoël reported a high speed distance relay in 1950[9] and subsequently electronic distance relay schemes were reported by Adams and Bergesth[10] in 1953 and Warrington[11] and Bergesth in 1954[12], the latter describing a distance relay on phase comparison principle. Further, Adamson and Wedepohl[13] reported a static mho distance relay in 1956 which provided excellent characteristic.

In the last two decades the developments in the field of static relays have been very fast and a number of new schemes have been reported. Static relays can be mainly classified as follows :

(i) Relays employing Amplitude comparators,
(ii) Relays employing phase comparators, and
(iii) Relays employing Hybrid comparators.

In the first class of relays employing amplitude comparators, the comparision of one or more quantities is carried out for the amplitude, ignoring the phase angular difference, with either a fixed reference or amongst themselves. The rectifier bridge type comparators initially developed in Norway, Germany and England employed the principle of amplitude comparison[9,14,15] . McLaren[16,17] extended the principle of instantaneous comparison of voltages and currents first described by Macpherson,McConnell and Warrington[6] to formulate a new sampling technique which allowed the comparison of the instantaneous values derived at different instants of time. Though the scheme employed the principle of amplitude comparison, the ultimate comparison, however, was carried out in a phase comparator. Further, though the scheme did not require to make use of phase shift or mixing of signals, still employed more involved circuitry. A new amplitude comparison technique has been reported by Khincha, Parthasarathy and Ashokkumar[18] which permits the comparison of the voltage and current at every instant eliminating the needs of special relay circuitry like zero-crossing detectors, sampling gates, amplitude-pulse duration convertors etc. An important problem in this class of relaying employing Amplitude Comparators is in designing the appropriate relay circuitry to maintain the waveform of the input signals till the final comparision for the amplitude is completed.

Due to the superior accuracy of the phase comparators, their development in the field of static relays appears to be more prominent. The phase comparators may be classified into (i) Cosine comparators, (ii) Sine comparators, and (iii) Sequence comparators.

A 2-input cosine comparator is supplied with mixed signals S_1 and S_2 as shown in 2-input comparator of fig.1.3 employed by Adamson and Wedepohl[13] . Signals S_1 and S_2 are compared in a coincidence circuit which produces a rectangular wave form, the duration of which is proportional to the positive coincidence of S_1 and S_2. This square wave

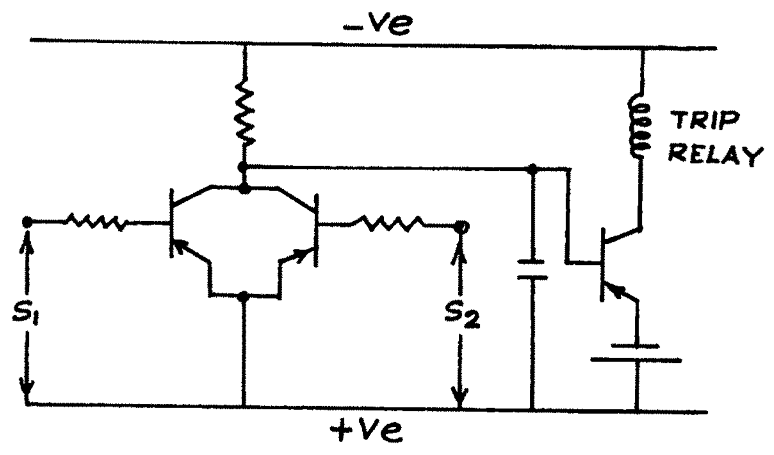


FIG. 1·3 2-INPUT COMPARATOR

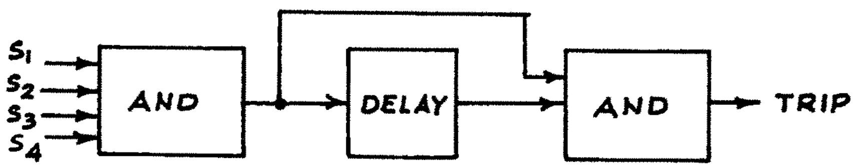


FIG. 1·4 BLOCK-SCHEMATIC DIAGRAM OF A MULTI-INPUT PHASE COMPARATOR is converted in-to a triangular waveform, by means of the integrating circuit, the peak amplitude of which provides the measure of coincidence. The level detector following the integrator circuit can be adjusted to provide tripping in any desired phase angular limits. This comparator although provided excellent mho characteristic, however, was not exploited commercially due to its inherent limitations. Nevertheless it laid foundation in the development of static relays.

Humpage and Sabberwal employed multi-input cosine comparator, first described by Vasquez and others[19], that resulted in economical construction. Fig. 1.4 illustrates multi-input cosine comparator in block-schematic form employed by Humpage and others[20] to obtain quadrilateral distance relay characteristic. The necessary inputs to the comparator to obtain the characteristic of fig.1.5(a)are:

$$\left.\begin{aligned} S_1 &= I_L Z_R - V_L \\ S_2 &= I_L X \\ S_3 &= I_L R \\ S_4 &= V_L \end{aligned}\right\} \quad \ldots\ldots (1.1)$$

Signals S_1 and S_2 are responsible for producing the segment CB of the characteristic. Similarly the pairs of signals S_2 and S_4, S_3 and S_4, and S_1 and S_3 yield the segments OA, OC and AB of the characteristic respectively.

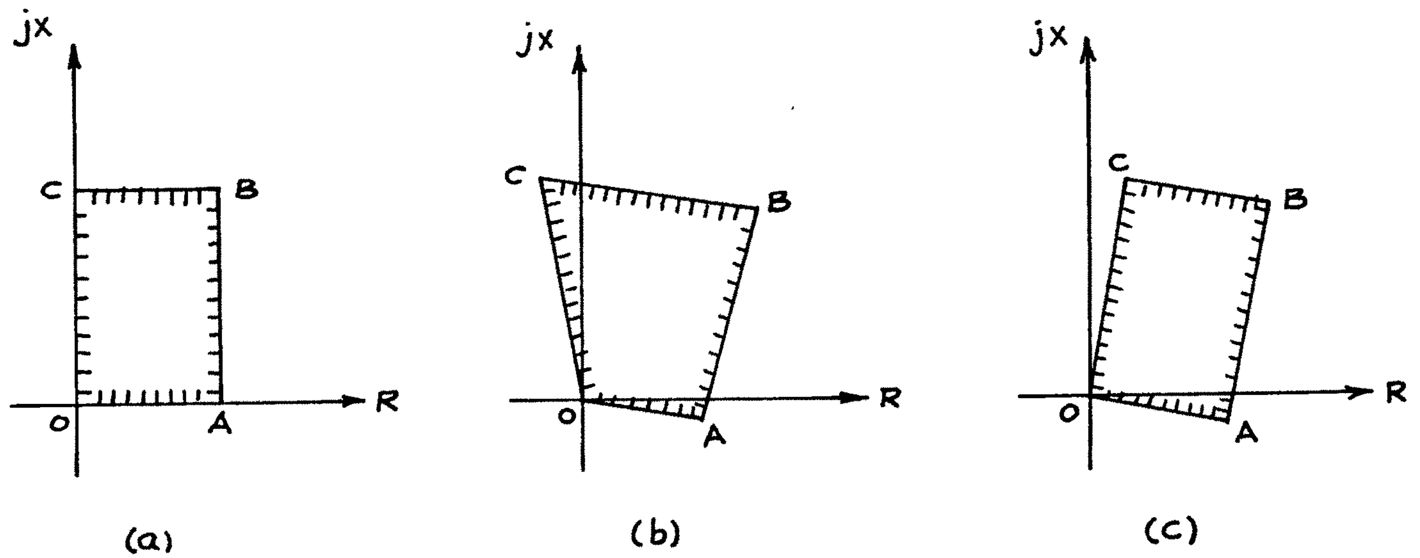


FIG. 1·5 QUADRILATERAL CHARACTERISTICS

The comparison between S_1 and S_2 yields mho characteristic which, however, does not affect the shape of the final quadrilateral characteristic as it gets contained within the quadrilateral.

Due to the unwanted 'interaction' amongst the signals it is not possible to obtain the preferred characteristic of fig.1.5(b) unless restricted limits of comparison are employed. In the meantime a compromise is to rotate the characteristic by an appropriate angle in the leading direction as shown in fig.1.5(c) by shifting V_L or I_L for the phase.

The multi-input phase comparator further described by Humpage and Sabberwal[20] employing unsymmetrical phase comparison limits provides improved versions of the characteristics. However, still in most of the cases it becomes difficult to eliminate the unwanted line segments appearing in the characteristic. Humpage and others have further explained the mathematical basis of this comparator, shaping of distance relay characteristics and their behaviour during various conditions of the system[20,21,22,23,24,25] The time of operation of the cosine comparator, in general, is high and do not provide the independent control of all the line segments of the characteristic. To improve the transient performance of the relay, Dual phase comparators and Double phase comparators working on block-block or block-average schemes have been reported[26,27,28,29].

In a 2-input sine comparator, a spike is derived at the zero cross-over of one of the signals (called operating signal) obtained from the system quantity or quantities and compared with the other signal for the phase difference. Dewey, Mathews and Morris[30] employed this type of comparator to obtain mho characteristic which provided the fastest measurement of direction. The transient performance of the relay has been verified by staged faults and field experience[31].

Parthasarathy[32] employed pulse technique in multi-input sine comparator to eliminate the unwanted segments and reported an improved distance relay that yielded the quadrilateral characteristic of fig. 1.6. Fig.1.7 illustrates the block-schematic diagram of the first zone relay. Signals V_L and I_L were applied to the measuring circuits (M) which produced the required signals S_1 through S_4 given by Eq.(1.2)

$$\left.\begin{aligned} S_1 &= I_L Z_R \angle \theta - \phi \\ S_2 &= V_L \\ S_3 &= V_L \angle -90^{o} \\ S_4 &= I_L R_F - V_L \end{aligned}\right\} \quad \ldots. (1.2)$$

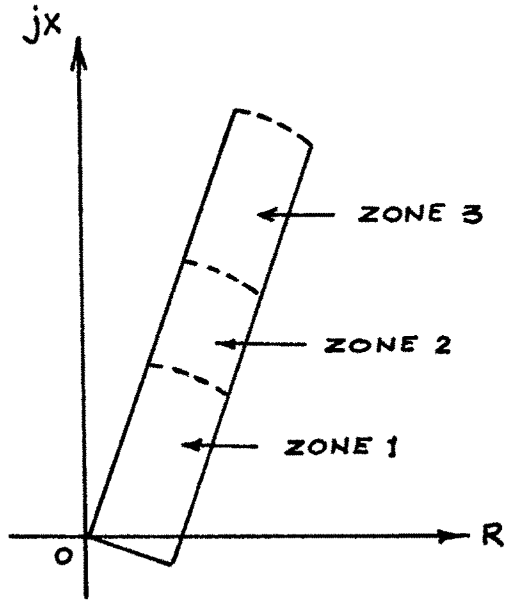


FIG. 1·6 3-STEP QUADRILATERAL CHARACTERISTICS

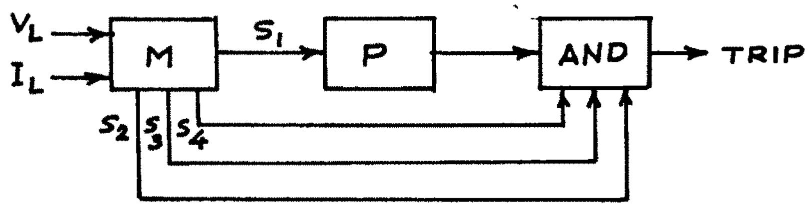


FIG. 1·7 BLOCK-SCHEMATIC DIAGRAM OF FIRST ZONE RELAY

Pulse forming circuit (P) was employed to obtain the pulse from S_1 at its zero cross over. This pulse was compared with the polarising signals S_2, S_3 and S_4 in the phase comparator, which was an AND gate. The phase comparator was arranged such that the phase comparison of S_1 took place with S_2, S_3 and S_4 individually. The comparison of S_1 pulse with S_2 and S_4 resulted in the sides of the characteristic in the form of blinder. The line segment furnishing the directional property to the characteristic was obtained from the comparison of S_1 pulse with S_3 . Since no interaction took place amongst the polarising signals S_2, S_3 and S_4, the unwanted segments in the tripping characteristic were eliminated.

Anilkumar and Parthasarathy[33] subsequently reported the mathematical basis of multi-input sine comparators taking into account only the symmetrical angular comparison limits.

The use of phase comparison principle is also made in sequence detection type single phase[34,35] and poly-phase[36,37,38] relays, and single phase relays incorporating ferrite cores[39,40].

The hybrid comparators listed as class (iii) in the above classification are combinations of amplitude and phase comparators wherein one type of comparator is supplied with one of its inputs from a comparator of the other type. Parthasarathy and others have employed this type of comparator in obtaining Conic[41] and quadrilateral[42] characteristics.

Eventhough a multi-input sine comparator yields characteristics with independent control of line segments and fastest measurement of direction, attempts were not made, hitherto, to foot these comparators on a generalised analytical approach. In addition, the design of the relays from the system requirement point of view and the necessity for the shaping of polar characteristics according to system conditions were not analysed.

In Chapter 2 of the present work, therefore, an account is given of the system conditions which influence the shape of the tripping characteristics under specific conditions.

In Chapter 3 the sine type comparators are analysed on a completely general basis. The analysis takes into account both symmetrical as well as unsymmetrical limits of phase comparison. Graphical constructions, both for circular as well as rectilinear characteristics, are developed to assist in the selection of necessary inputs to the comparator to obtain desired characteristics. From these mathematical basis a comparative assessment of

2-input and multi-input comparators is made to appreciate the flexibility in the choice of necessary signals for the comparison to arrive at the desired characteristics. A multi-input comparator model is subsequently described which yields composite distance relay characteristic using unsymmetrical phase comparison limits.

A direct approach in the selection of appropriate signals to obtain a desired pick-up characteristic is, further, explained in Chapter 4 which employs the principle of sequence comparison. A 3-input sequence detector is developed on this basis and is employed to obtain a typical quadrilateral characteristic. Two schemes of 3-step relay arrangements are also included.

Chapter 5 of the present work is devoted to report some developments in the hybrid comparison techniques. These techniques yield conic characteristics and make possible the incorporation of a thyristor in the output stage for rendering the relay completely static.

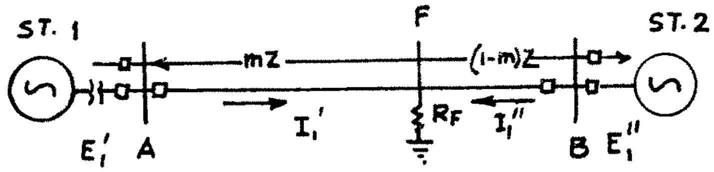
Distance relays are usually employed in 3-step operation to provide primary and back-up protection to the line under consideration. The first and second zone distance relay characteristics are required to be directional. The relays yielding these characteristics are likely to loose the directional property during close-in faults due to the collapse of the bus-voltage. The practice, therefore, is either to supplement one of the polarising signals of the relay with the one derived from the voltage of healthy phase or phase pair or to use resonant circuits giving memory action. Chapter 6 of the present work is completely devoted to report the effects of level of polarisation and the system conditions on the comparator models developed in the present work.

The effect of external polarisation helps in enlarging the pick-up characteristics of phase comparators during unbalanced faults only. However this desired effect is not pronounced for low Z_S / Z_L ratios which occur in EHV systems and for three phase faults. Hence an attempt has been made in Chapter 7 of the present work to present the development of a new self-adjusting relay. This relay remains adequately stable during external forward faults, reverse faults, healthy and over-load conditions of the system, power-swings and faults on the other phase or phases. It's characteristic bulges only during faults and can accommodate more fault resistance due to the automatic adjustment in the shape of the characteristic.

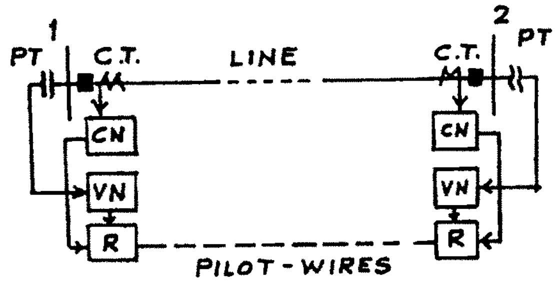
The literature on pilot-wire differential protection system of short transmission lines show marked developments in the last decade. The trend appears to be on the replacement of electro-mechanical relays by their solid-state counter parts. In continuation of this trend, some developments in the application of semi-conductor devices to this mode of protection are reported in Chapter 8 of the present work.

A very limited use of distance relays has been hitherto made in the protection of short transmission lines. In 1968 Kliman[43] reported a novel method of protection of short transmission lines, called ' Restricted zone protection ' . In this scheme the difference of positive sequence voltages at the two ends of the protected circuit is compared with the positive sequence current of the local end, the positive sequence voltage of the remote end being obtained by means of pilot wires. The comparison is carried out in an impedance unit, and the mode of protection essentially terminates into that of distance measurement. Fig.1.8 shows the comparison scheme in block-schematic form.

From fig.1.8 it may be observed that during healthy and over-load condition of the system, and faults external to the protected section the impedance seen by the relay at station 1 will be



(a) TYPICAL POWER SYSTEM



(b) SCHEME OF PROTECTION

CN - POSITIVE SEQUENCE CURRENT NETWORK
VN - POSITIVE SEQUENCE VOLTAGE NETWORK
R - RELAY

FIG. 1·8 TYPICAL POWER SYSTEM AND SCHEME OF PROTECTION

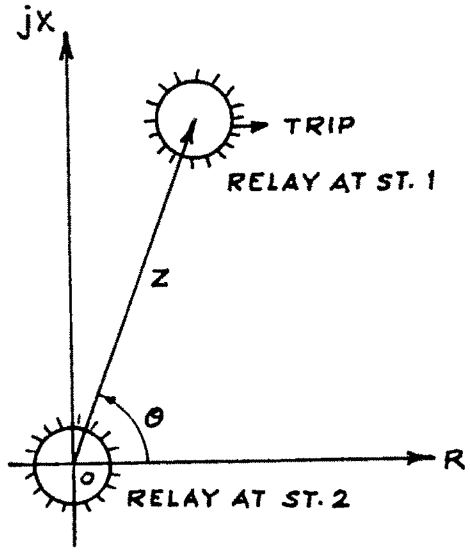


FIG. 1·9 CIRCULAR CHARACTERISTICS

$$Z'_{r_1} = (E'_1 - E''_1) / I'_1$$

$$= Z \qquad \ldots\ldots \quad (1.3)$$

where Z is the line impedance.

During internal faults the relay at station 1 will measure the impedance given by eq.(1.4)

$$Z'_{r_1} = Z \; [m + K(m-1)] \qquad \ldots\ldots \quad (1.4)$$

where the relaying current distribution factor K is defined as

$$K = I''_1 / I'_1 \qquad \ldots\ldots \quad (1.5)$$

Employing expressions (1.3) and (1.4) Kliman suggested the characteristic of fig.1.9 for the protection of the line. Tripping must be effective outside this circular characteristic, which should have radius equal to about 0.1Z .

This analysis although provides new concept in line protection, however, is not complete in that only scalar values of relaying current distribution factor were considered and the attenuation and phase-shift introduced in the relayed signals by the pilot-wires were ignored.

Two schemes of restricted zone protection are presented in Chapter 9 of the present work. In the first scheme the comparison is carried out between the quantities similar to those of Kliman's scheme. In the second scheme the positive sequence voltage at the local end is compared with the positive sequence current of the remote end. In both cases, the analysis is carried out taking the complex nature of relaying current distribution factor into account. The attenuation and phase shift introduced in the relayed signal by the pilot link are also considered. Further the power swing equations are developed from fundamental considerations and swing loci are plotted. From this analysis, the shape of the stable zone suggested by Kliman is shown to be unacceptable. The alternative characteristics are suggested and finally relay comparator models are described in block-schematic form to realise the suggested stable zones.

The relay models developed in the present work have been subjected to tests using the protective testing facilities developed by Hamilton and Ellis[44]. Design principles and typical discriminating and logic circuits are described in the main text. The performance of the models subjected to reduced scale laboratory investigation and measurements, have been described in the appendices.

The important conclusions drawn from the work are summarised in Chapter 10.