STATIC PROTECTIONS FOR PARALLEL FEEDERS

By
SATISH PARTI

A Dissertation
submitted in partial fulfilment
of the requirements for the Degree
of
MASTER OF ENGINEERING
in
ELECTRICAL POWER SYSTEMS

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE
1965

CERTIFICATE

CERTIFIED that the dissertation entitled " STATIC PROTECTION FOR PARALLEL FEEDERS", which is being submitted by Sri S. C. Parti in partial fulfilment for the award of Degree of Master of Engineering in "Power Systems" of University of Roorkee, Roorkee is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

This is further to certify that he has worked for a period of 9 months, from Sept 1964 to May 1965 for preparing thesis for Master of Engineering Degree at the University of Roorkee, Roorkee.

T.S.M. Rao.

(T.S.M.RAO)
Prof. & Head
Department of Electrical Engg.
Regional Engineering College,
JAIPUR.

Dated: 9.9.65
September, 1965

ACKNOWLEDGEMENTS

I humbly express my gratitude to Dr. T.S.Madhava Rao, formerly Associate Professor in electrical engineering University of Roorkee, Roorkee for his continued guidance and discussions in preparation of my dissertation work.

I am also indebted to Prof. C.S.Ghosh for providing the required facilities in the department in connection with my work.

I express my thanks to my collegues Messrs S.C. Gupta, T.Subba Rao for their valuable help.

Satish Parti
Satish Parti.

Roorkee
19.9.65.

SYNOPSIS

The growth of the use of parallel feeders has been rapid due to increased reliability of service and to the relative ease of obtaining selectivity. This dissertation is an attempt for the protection of parallel feeders by static means (d.c. bridge). Operating characteristics similar to electro-mechanical balance-current relay have been developed using rectifier-bridge amplitude comparator. The high speed parallel feeder protective-gear, and development of static relays have been reviewed and other static schemes suggested by various authors are explained. Thereafter complete design of the scheme developed by the author is given in detail. In conclusions definite advantages are claimed for this scheme over other schemes.

-O-

CONTENTS

-0-

INTRODUCTION

The importance of automatic protective devices has grown with the size of transmission systems. In recent years great advances have been made in the design and construction of the protective devices, and present day types can be relied upon in practically all concievable cases of electrical distresses. Several new types of protective relays have been developed in particular, the transductor relay, a new type of moving coil relay, and a polarised moving iron relay. These developments are closely associated with an important trend towards the use of static equipment for sorting out of information and the comparison of quantities.

It is however fortunate that in recent years, new devices such as transistors and other semi-conductors have become available. The advent of these devices opens the way to new designs of protection schemes which combine the experience gained over the last ten years with new freedom of approach of great potential value.

The most important measurements in selective protection engineering are :

1. Distance Measurement.
2. Measurement of Direction.
3. Differential Protection.

Basically three different methods of measuring are feasible and these are :

(a) Comparison of the square values of vector quantities (Torque comparison).

(b) Phase angle relationship between vector quantities

(c) Comparison of the numerical values of vector quantities (d.c. Bridge).

This dissertation deals with an attempt for the protection of parallel feeders by static means utilising bridge-rectifiers for the comparison of the numerical values of vector quantities. The growth of the use of parallel lines (usually in pairs) has been rapid due to increased reliability of service and to the relative ease of obtaining selectivity and high speed of the relay protective systems. In d.c. bridge method the Selinium rectifiers are used as multi-input comparators supplying an electromagnetic slave-output relay of moving coil type for final tripping.

Investigations into the working of multi-input comparators have been done by Hoel(1) in the year 1950. He has shown that for a moving coil relay, with three or more coils energised from fully rectified currents i_1, ..., i_n, the relay operates according to the relation

$\pm|i_1|\pm|i_2|\pm$ ---------- $\pm|i_n| \gg 0$ in an ideal case.

The ± sign indicates that the rectifiers are connected either in the operate or restraint direction. Basing on this a practical relay of Balanced-current type characteristics has been developed by the author. Other protective schemes by different authors for the static protection of parallel feeders have been reviewed and some definite advantages are claimed for the scheme usedby the author.

-0-

CHAPTER 1

HIGH SPEED PARALLEL FEEDER PROTECTIVE GEAR.

1.1. FACTORS AFFECTING THE CHOICE OF FEEDER PROTECTIVE-GEAR:

Recent developments in feeder protection have been mainly towards highly discriminative protective-gear alongwith short fault clearance times. This is essential because modern operating conditions demand that when faults occur they should be cleared as rapidly as possible inorder to ensure system stability and further, only faulty section should be disconnected to ensure continuity of supply.

Considerable progress has been made during recent years in circuit breaker design, enabling total break times of 0.06 to 0.08 seconds(i.e. the time from energising of the trip coil to complete arc extinction).

It is therefore most important that protective-gear operating times of 0.02 to 0.04 seconds be obtained in certain instances to ensure complete fault clearance time of the order of 0.1 to 0.2 seconds.

Feeder protective systems which satisfy the above conditions are :

a. Pilot-wire Protective Systems.
b. Carrier current systems.
c. Non-pilot-wire Protective Systems , such as
    i. High Speed definite impedance Protection.
    ii. High Speed parallel feeder Protection.

Although pilot-wire systems offer excellent relaying characteristics, its application is unfortunately restricted due to high cost of providing pilot wires.

Carrier systems are expensive since the apparatus required for injecting the carrier impulses into the power lines has to be insulated for the full system voltage. Furthermore, a large amount of ancillary apparatus is required, such as transmitting and receiving units with their associated batteries, chargers etc; necessitating considerable testing and maintenance.

The recent improvements in the design of distance relays towards instantaneous operation for faults upto 90 percent of feeder length is making them increasingly popular for providing primary protection of parallel feeders. Until recently distance relays are used to afford the necessary backup feeder protection when the primary parallel feed relay system is out of service during single circuit operation.

High speed parallel feeder protection gives fast operating times for faults in the protected feeder zone and no costly pilot wires are required. Consequently where feeders are run in duplicate, the parallel feeder relay systems can function on the balanced current principle comparing magnitudes of current only, or on the balanced-power principle comparing magnitude and direction of power flow. The balanced-current is relatively simple in construction as no directional elements are necessary and possesses a high stability ratio, but its application is restricted to the transmitting end of parallel feeders where the unbalancing is occasioned by phase to phase or ground faults in either line. The balanced-current system may also be used

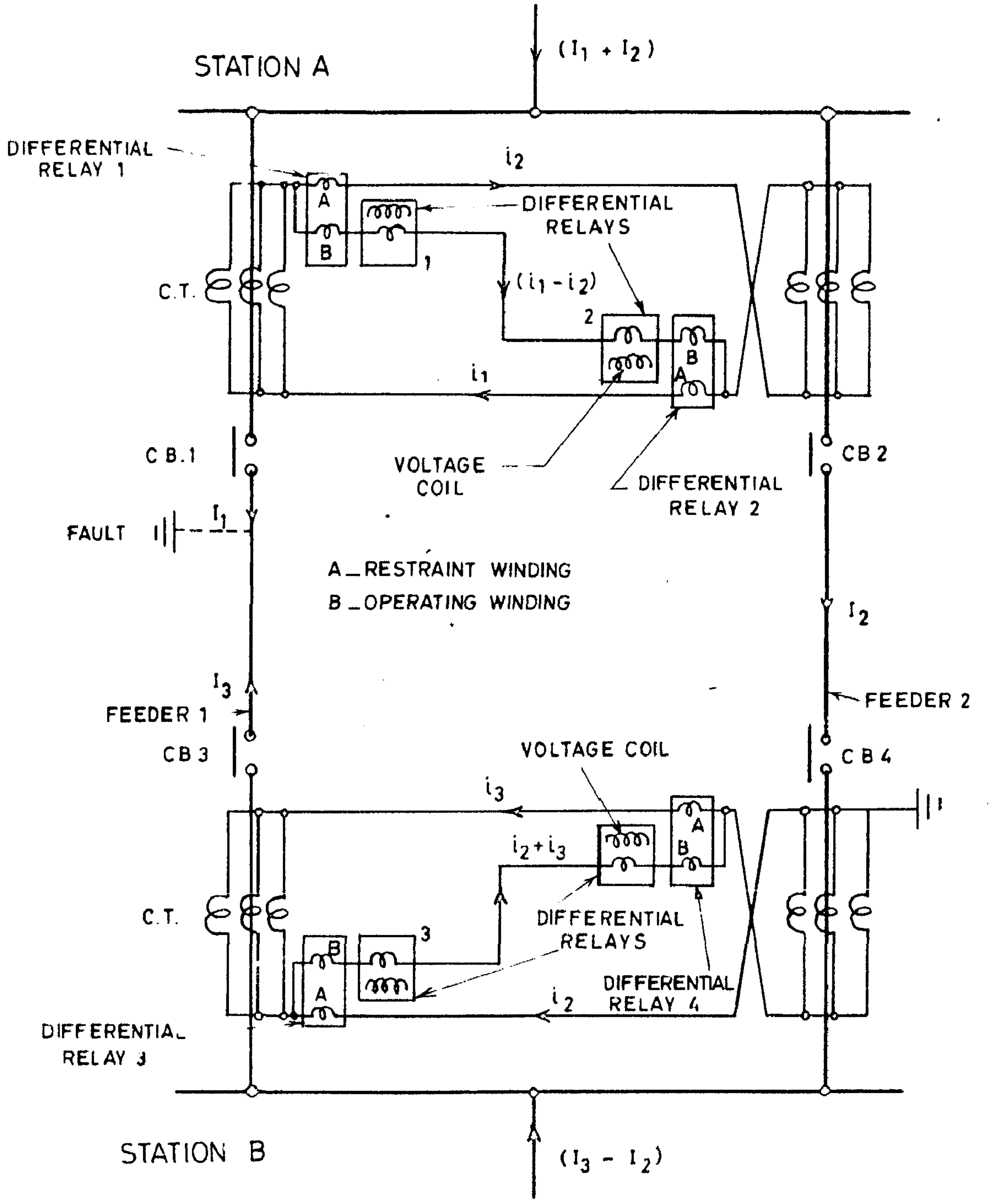

STATION A
$(I_1 + I_2)$
DIFFERENTIAL RELAY 1
i_2
A
B
DIFFERENTIAL RELAYS
1
$(i_1 - i_2)$
C.T.
2
B
A
i_1
C B.1
C B 2
VOLTAGE COIL
DIFFERENTIAL RELAY 2
FAULT
I_1
A _ RESTRAINT WINDING
B _ OPERATING WINDING
I_2
I_3
FEEDER 1
FEEDER 2
CB 3
C B 4
VOLTAGE COIL
i_3
A
$i_2 + i_3$
B
C.T.
3
B
DIFFERENTIAL RELAYS
A
DIFFERENTIAL RELAY 4
i_2
DIFFERENTIAL RELAY 3
STATION B
$(I_3 - I_2)$

FIG.1

for the protection at the receiving end of parallel lines provided there is an additional source of power supply at the receiving end which will increase the fault current in defective line at least 10 to 25 percent. In general at the receiving end where a reversal of power can occur under fault conditions, a balanced power scheme should be adopted. When transmitting and receiving ends are not clearly defined such as in inter-connected and ring systems, it is always preferable to employ balanced power relays.

1.2. HIGH SPEED PARALLEL-FEEDER PROTECTIVE GEAR (2,3,4,5)

The majority of the faults on overhead lines involve one phase and earth, and for convenience and economy the parallel feeder protective gear, need only cover faults involving one phase and earth, leaving the back-up protective gear to take care of faults between phases.

The connections of the current circuits for duplicate feeders are shown in Fig. 1 . The apparatus required comprises, a set of three current transformers, a differential relay, and a directional relay at both ends of each feeder. A voltage supply is required for directional relay. Differential relay is of high-speed balanced beam type. Directional relay is of the Wattmetric type. The supply for the voltage coil of the directional relay is derived from an open delta secondary winding of a three phase transformer, the primary of which is connected in star-with neutral point earthed. The secondary voltage will be equal to the vector sums of the three leg voltages, the resultant under healthy conditions being zero. Assuming a

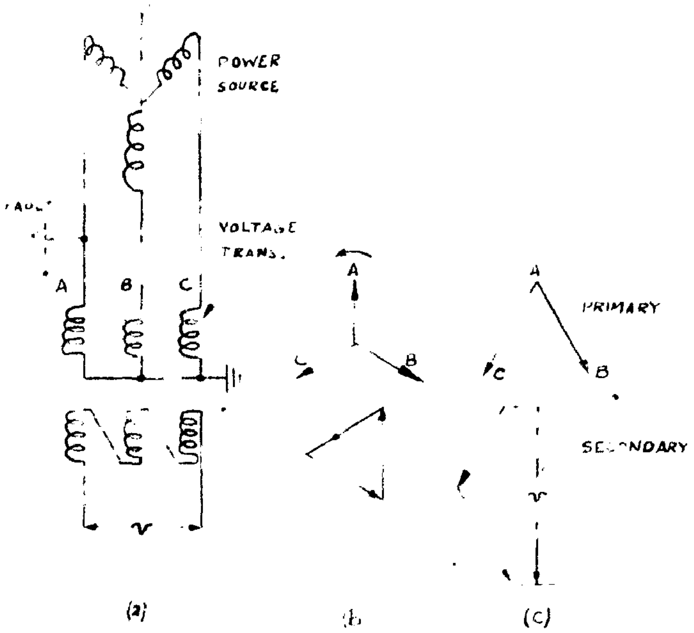


FIG. 2

Star/open delta voltage transformer showing connections and secondary voltage under healthy and earth fault conditions.

(a) V.T. connections
(b) V.T. primary and secondary voltages under healthy conditions.
(c) V.T. primary and secondary voltages for earth fault on phase A.

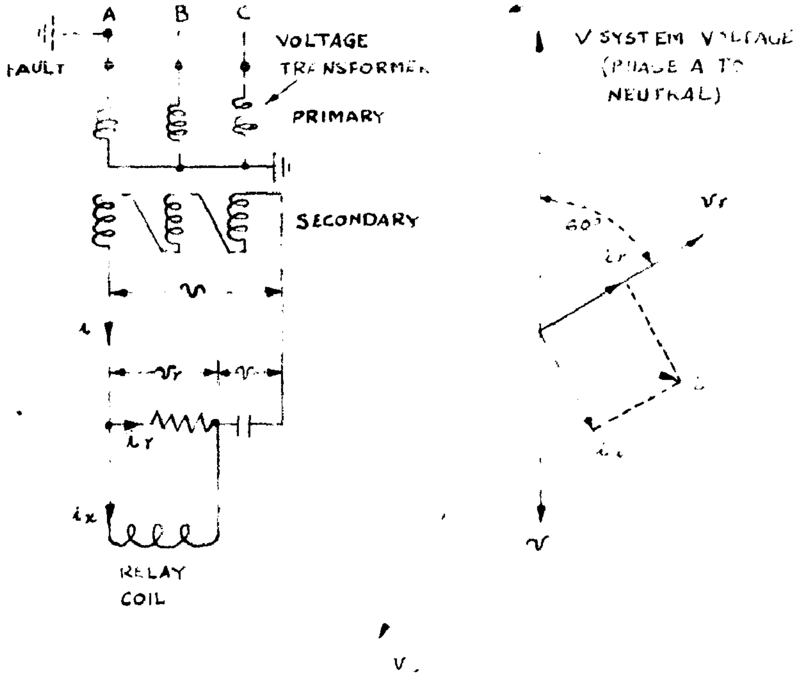


FIG. 3

Vector relationship of primary and compensated secondary voltage.

(a) Connections
(b) Primary and secondary voltage for an earth fault on phase A.

fault on the "A" phase, it is clear that the "A" phase of the voltage transformer is short circuited (or partly so) according to the distance of the fault from the point of connection of the voltage transformer; consequently, the voltage impressed across the two remaining phases rises to some value approaching phase to phase voltage. The resultant secondary voltage under this condition approaches three times the normal secondary leg voltage, and is in phase opposition to the primary voltage to earth of the "A" phase.

Fig. 2(a) shows the primary and secondary voltages of the voltage transformer under healthy conditions, while Fig. 2(b) shows the vectors, assuming an earth fault on the "A" phase close to the voltage transformer.

<u>Phase Angle Compensation</u>:

It is also necessary to compensate for the power factor of the fault to ensure maximum torque to give fast and effective operation for any earth fault condition.

The neutrals of 132 and 66 KV systems are generally solidly earthed, the fault power factor is therefore dependent upon the impedance of fault path. This is mostly reactive and the fault current lags the voltage by approximately 90°. Due to this reason, with solidly earthed systems, it is usual to compensate the voltage applied to the directional relay so that it lags the primary voltage by approximately 60°.

Fig. 3(a) shows the connections of a compensating resistance - capacitance network, whilst fig. 3(b) shows vector relationships of currents and voltages.

It will be seen that the voltage v_r across the relay leads the voltage transformer secondary voltage by 120° i.e. lags the primary voltage of the faulty phase by 60°.

1.2.1. Operation of the Protective Gear :

Fig. 1 shows primary and secondary currents for a fault as feeder 1 close to station "A". For this condition the operation will be as follows :

a. STATION 'A':

The current i_2 in the restraining coil of feeder 1 differential relay is proportional to the fault current I_2 in feeder 2. Similarly, the current in the restraining coil of feeder 2 differential relay is proportional to I_1. The currents in the operating coils of both differential relays and directional relays are proportional to $I_1 - I_2$ hence the differential relay on the feeder carrying the higher current tends to operate whilst the other does not.

The direction of the resultant current through the current coils of the directional relays is such that the relay associated with the feeder carrying the higher current operates while the other does not. It is clear therefore that the protective gear on feeder 1 operates unless the fault current in the two feeders approaches equality. If this is so, the protective gear at station "A" remains in-operative until that at station "B" operates, thereby opening $C.B_3$ and reducing I_2 to zero.

(b) STATION "B"

The operating coils of the differential relays and also the current coils of directional relays, carry a current proportional to the sum of current in each feeder $(I_2 + I_3)$. The current in the restraining coil of feeder 1 differential relay is proportional to the fault current I_2 in feeder 2. Similarly, the current in the restraining coil of feeder 2 differential relay is proportional to I_3. Both differential relays therefore operate, but owing to the direction of the current in the directional relays the one associated with feeder 1 operates while that associated with feeder 2 does not. Circuit-breaker $C.B_3$ is tripped, the fault is isolated and healthy conditions are restored.

When a fault occurs outside the protected zone, both feeders carry current of equal magnitude and in the same direction. Theoretically no current should flow in the operating element of the differential relays or the current coil of directional relays. In practice, a small current may be present during heavy through-faults due to dissimilarity between the current transformers. The restraining coils of the differential relays or feeder 1, however, carry a current proportional to the fault current in feeder 2 whilst the restraining coil of the relay on feeder 2 carry a current in feeder 1 i.e. approximately one-half of the total fault current. Furthermore, no current flows in the current coil of directional relays, so that none of the protective relay operates.

The stability of protective gear on through-fault is therefore assured by two distinct functions i.e. the restraining effect on the differential relays and the non-operation of the directional relays.

1.3. SINGLE LINE OPERATION:

When one feeder is not in use, it is obvious that the parallel feeder protective gear on the second feeder must be rendered in-operative leaving only the back-up protection in service . This feature is obtained by automatically switching the tripping circuits. The tripping circuit from the parallel feeder protective relays on one feeder is controlled by an auxiliary switch on the circuit breaker associated with the other feeder, so that when one feeder is out of use, the tripping circuit of the feeder in service is broken. The tripping circuit (28) is shown in fig. 4

The directional contacts are connected in series with the differential contacts in the tripping circuit and they serve as the interlock.

1.4. DISTANCE PROTECTION OF THE PARALLEL LINES (17,18,26)

It has been mentioned previously, that there is an increasing trend towards using distance relays for the protection of parallel feeders.

There are two ways in which the distance protection of parallel lines can be carried out.

1. Instaliation of seperate protection on each line reacting to current in that particular line only. The setting of the relays is adjusted as in the ordinary course of single line operation. The first zone is set to cover 80% of protected line. Second zone is set to cover protected line plus 50% of the next line section and third zone is set to cover protected line plus 125% of the next line section.

2. General protection on two lines, reacting to the sum of the currents in the lines.

The first method has the advantage that impedance presented at the terminals of the ohm relays of the faulty lines does not depend upon whether one or more than one line is working.

However with the second method, in order to ensure equal impedances at the terminals of the ohm relays when one or two lines are working, it is essential to vary the voltages applied to the relay twice.

When second method of distance protection is used, the impedance at the terminals of the Ohm relays as a function of the point of fault is given by the curves shown operates.

The stability of protective gear on through-fault is therefore assured by two distinct functions i.e. the restraining effect on the differential relays and the non-operation of the directional relays.

1.3. SINGLE LINE OPERATION:

When one feeder is not in use, it is obvious that the parallel feeder protective gear on the second feeder must be rendered in-operative leaving only the back-up protection in service. This feature is obtained by automatically switching the tripping circuits. The tripping circuit from the parallel feeder protective relays on one feeder is controlled by an auxiliary switch on the circuit breaker associated with the other feeder, so that when one feeder is mut of use, the tripping circuit of the feeder in service is broken. The tripping circuit(28) is shown in fig.4

The directional contacts are connected in series with the differential contacts in the tripping circuit and they serve as the interlock.

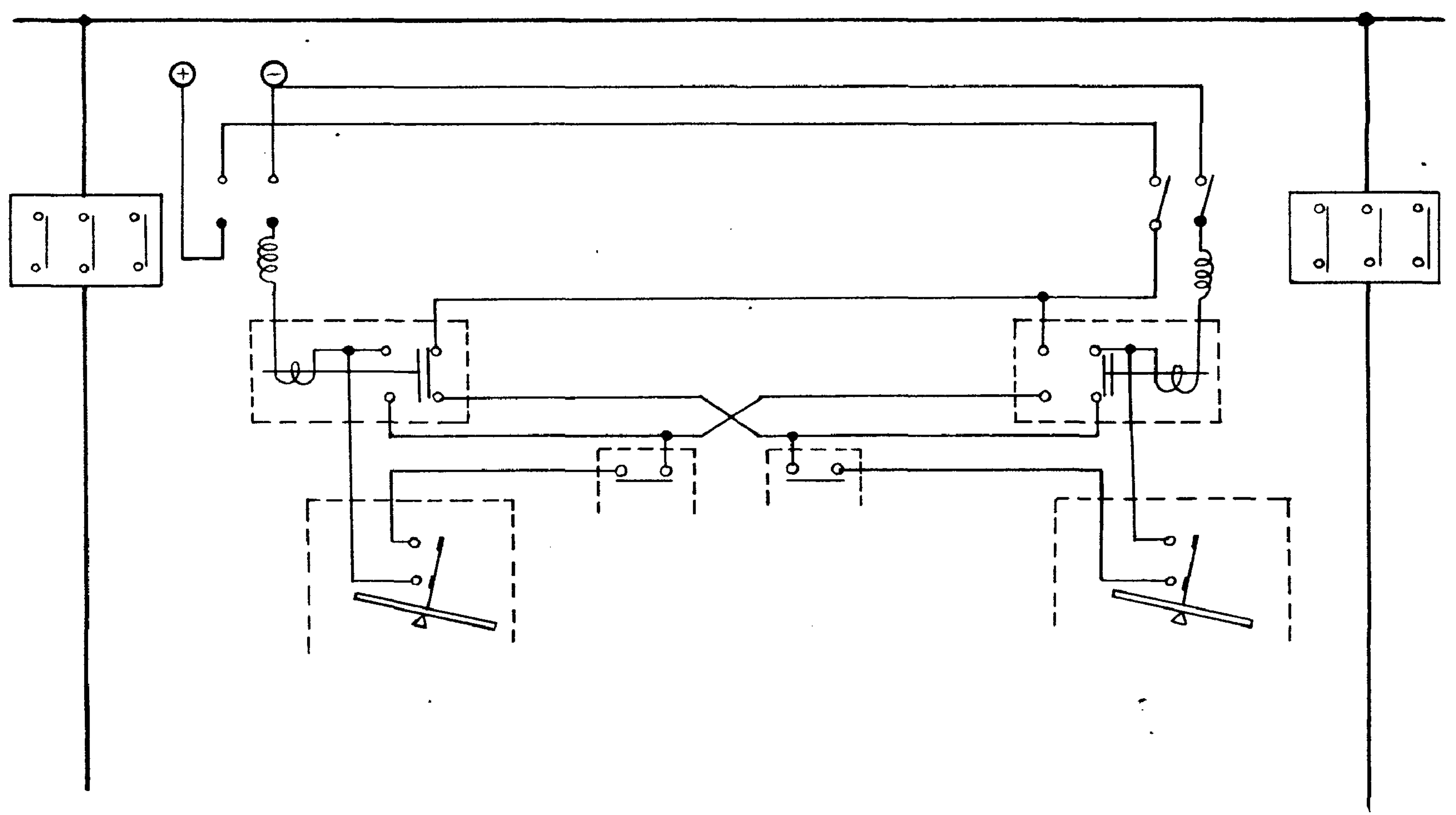


Fig 4 TRIPPING CIRCUIT

1.4. DISTANCE PROTECTION OF THE PARALLEL LINES (17,18,26)

It has been mentioned previously, that there is an increasing trend towards using distance relays for the protection of parallel feeders.

There are two ways in which the distance protection of parallel lines can be carried out.

1. Installation of seperate protection on each line reacting to current in that particular line only. The setting of the relays is adjusted as in the ordinary course of single line operation. The first zone is set to cover 80% of protected line. Second zone is set to cover protected line plus 50% of the next line section and third zone is set to cover protected line plus 125% of the next line section.

2. General protection on two lines, reacting to the sum of the currents in the lines.

The first method has the advantage that impedance presented at the terminals of the ohm relays of the faulty lines does not depend upon whether one or more than one line is working.

However with the second method, in order to ensure equal impedances at the terminals of the ohm relays when one or two lines are working, it is essential to vary the voltages applied to the relay twice.

When second method of distance protection is used, the impedance at the terminals of the Ohm relays as a function of the point of fault is given by the curves shown in Fig 5 . These impedance curves for 3-ϕ short circuit are derived as follows

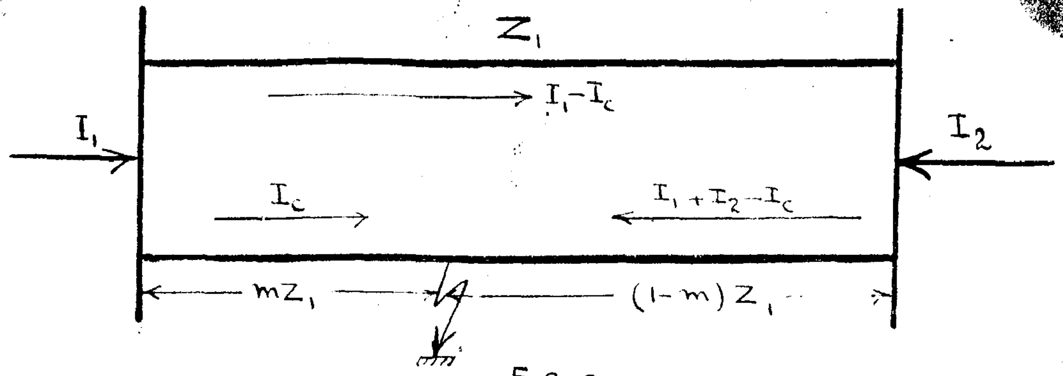


Fig 6

Z_1 = impedance of the line

m = Proportion of the line impedance from station A to the point of short circuit.

Considering the voltage between A and B and ignoring mutual impedance between feeders referring to Fig. 6 we have

$$(I_1 - I_o) Z_1 + (I_1+I_2-I_o)(1-m)Z_1 = I_o m Z_1$$

$$I_o = \frac{-I_1(mZ_1-2Z_1) - I_2(mZ_1-Z_1)}{2Z_1}$$

Fault voltage $V_F = I_o m Z_1$

$$= \tfrac{1}{2}\left(- I_1 m(mZ_1-2Z_1) - I_2 m(mZ_1-Z_1) \right)$$

$$= I_1 mZ_1 - \frac{I_1 m^2 Z_1}{2} - \frac{I_2 m^2 Z_1}{2} + \frac{I_2 m Z_1}{2}$$

The impedance at the ohm relay terminals $= Z = \dfrac{V_F}{I_1}$

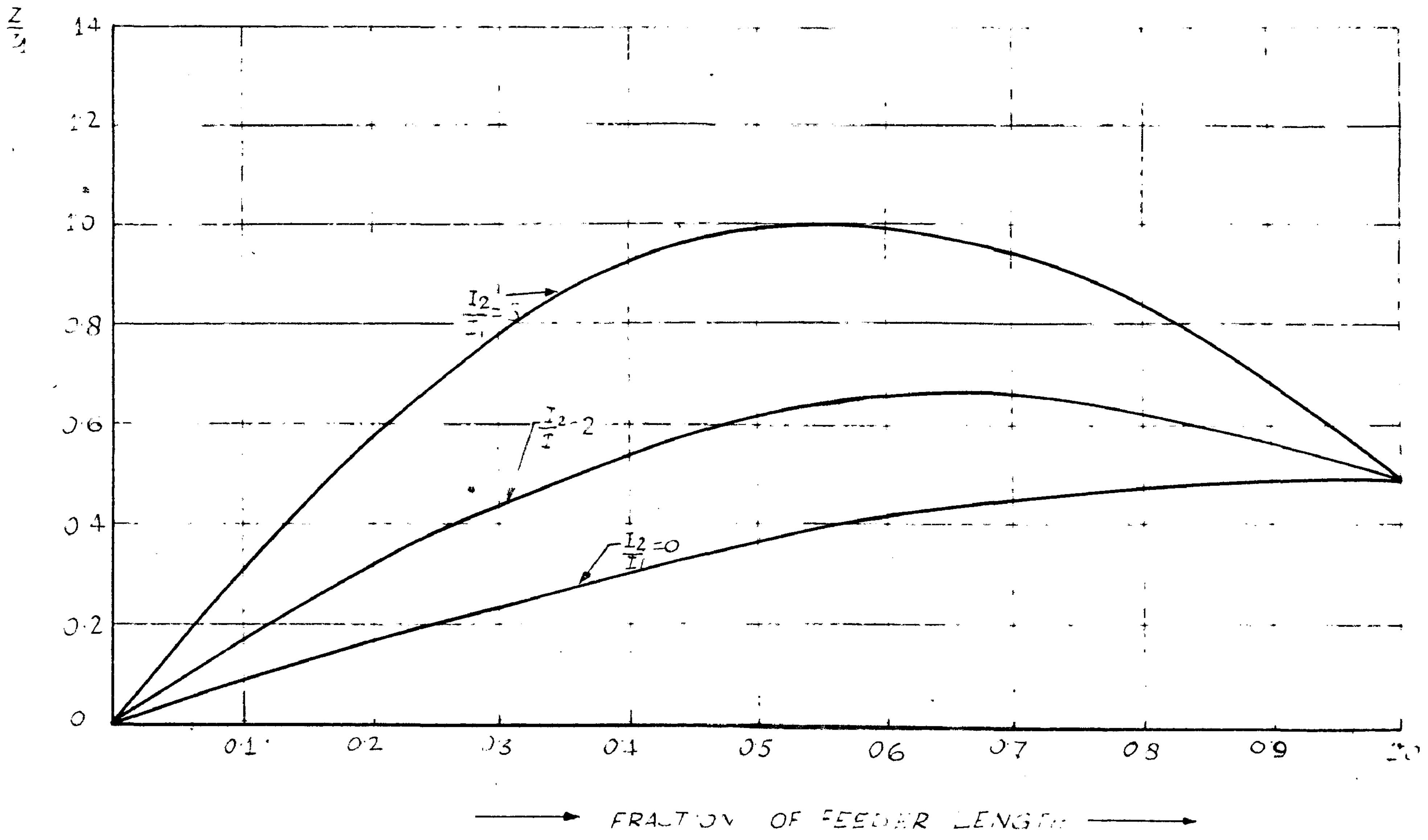

Z/Z
1·4
1·2
1·0
0·8
0·6
0·4
0·2
0
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1·0
I2/I1 =
I2/I1 = 2
I2/I1 = 0
FRACTION OF FEEDER LENGTH

FIG. 5

$$\therefore Z = mZ - \frac{m^2 Z_1}{2} - \frac{I_2 m^2 Z_1}{I_1 2} + \frac{I_2}{I_1} m \frac{Z_1}{2}$$

$$= \left[2 + \frac{I_2}{I_1} - m \left(1 + \frac{I_2}{I_1} \right) \right] \frac{m}{2} Z_1 \qquad ——(1)$$

Assuming I_1 and I_2 to coincide in phase then equation (1) gives impedance curves for given relationships of the currents I_1 and I_2 from both ends to the protected line . These impedance curves indicate that maximum impedance at the relay terminals can occur when there is short circuit within the limits of protected section, but not at its ends. Secondly the impedance at the relay terminals is reduced to the extent that fault is moved away.

When there are faults on one of the parallel lines and failure to operate occurs, or there is no basic protection (e.g. transverse differential protection), the distance protection trips only the faulty line.

When protection is given in the second way, both lines are tripped.

1.4.1. EFFECT OF THE MUTUAL IMPEDANCE BETWEEN PARALLEL CIRCUITS OF DOUBLE AND MULTI-CIRCUIT LINES ON THE LAYOUT AND ACCURACY OF DISTANCE RELAYS (17, 18)

The problem of mutual induction between parallel circuits arises when unbalanced faults occur on one line causing induced voltages in the parallel circuit. The mutual induction resulting from the flow of positive sequence current is small and is reduced to negligible value by the transposition of the conductors. However when two overhead lines are operating in parallel and an earth-fault occurs on one of them, the zerophasesequence network requires modifications because of mutual inductance between the two circuits caused by the flow of zero sequence currents whose vector sum is not zero. The mutual inductance between circuits carrying zero sequence current may vary from zero for widely seperated circuits to 75% of the self-inductance in the case of double circuit line. A mutual inductance of the order of 50% or greater is far from negligible in determining the distribution of flow of current in parallel circuits.

Figure 7 shows the modified impedance diagram for the purpose of calculating the flow of zero sequence current whenever two circuits have mutual zerosequence inductance and are electrically connected at both ends.

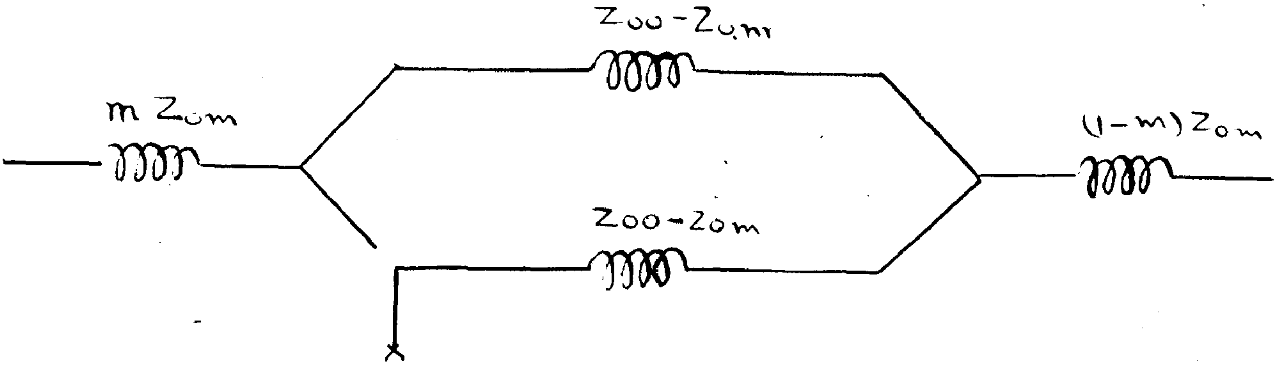


FIG.7 ZERO SEQUENCE DIAGRAM

With the modifications in the zero sequence network of the double circuit line, the conventional type distance relays are not able to measure 3earthfaults with their true impedance. The resulting measurement error observed in the distance relay closet to the earth-fault , depends upon the location of the fault, of the infeed points and of the neutral earthing points. These measurement errors result in terms of fault impedance giving either too great or too short a distance. These conditions can be studied by considering an earthfault on a double circuit line as shown in Fig. 8(a) . The sequence diagram with such fault fed from both ends is shown in Fig. 8(b) .

In Fig. 8(b) suffixes I and II denote the faulted and sound system of the line respectively, A and B the infeeding points, Z_{om} the mutual impedance of the line

m = proportion of the line from station A to the point of short circuit.

Z_{1_I} = Positive sequence impedance of line I

$Z_{1_{II}}$ = Positive sequence impedance of line II.

V_{R_A} = Phase voltage at Station A

I_{R_A} = Current conveyed by the faulty conductor R

I_o = Zero sequence component of current.

Z_{oo} = Zero sequence impedance of the line.

I_M = $I_R + I_Y + I_B$ = residual current = $3\ I_o$

$I_{M_{AI}}$ = $3I_{o_{AI}}$ = Residual current in faulty system I

$I_{M_{AII}}$ = $3I_{o_{AII}}$ = Residual current in sound system II

K_1 = Compensation factor = $\dfrac{Z_{oo}/Z_1 \quad - 1}{3}$

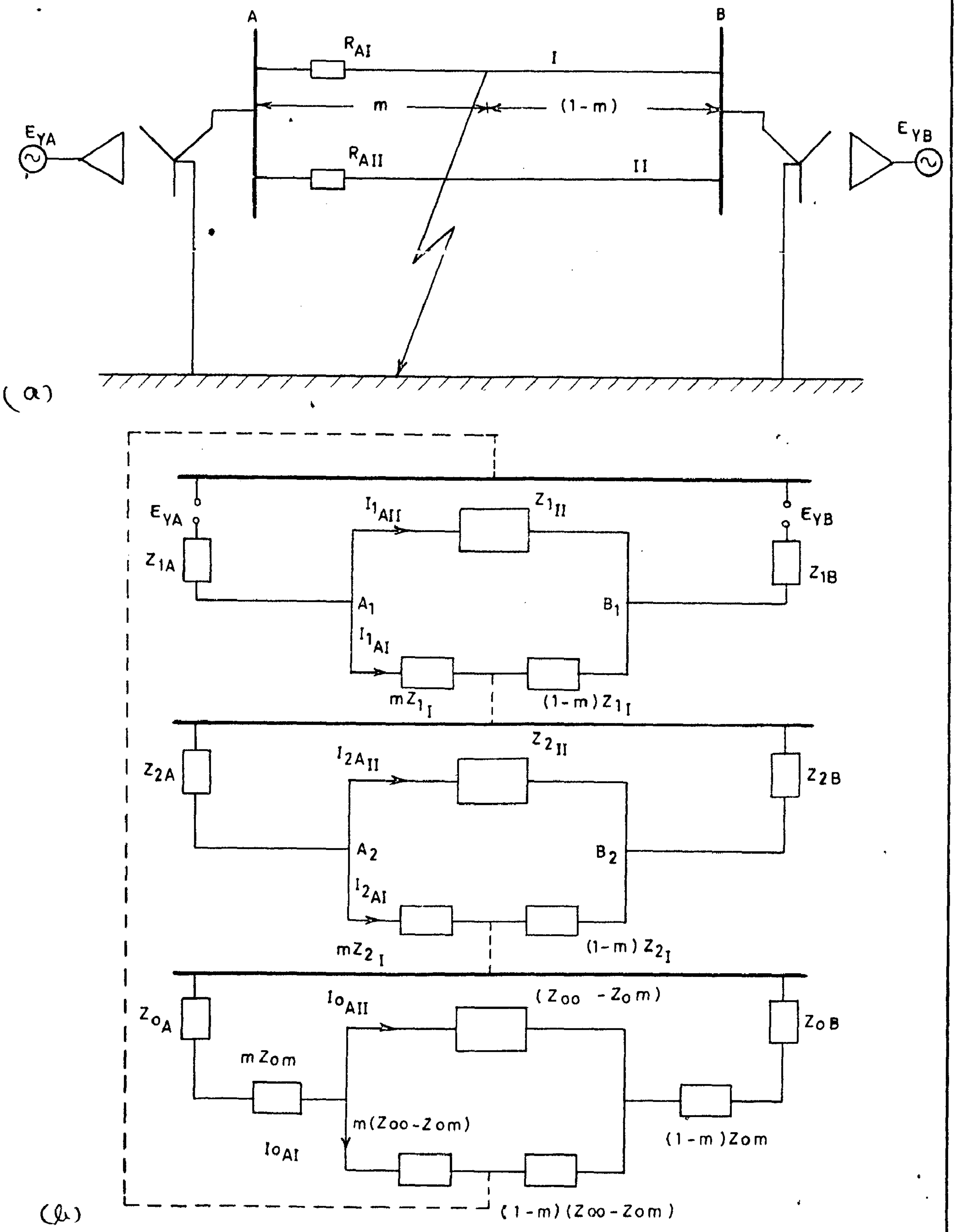


FIG. 8 SEQUENCE DIAGRAM

K_2 = Residual current factor or compensation factor of the sound system II

$Z_{M_{AI}}$ = The impedance measured by distance relay R_{AI} in accordance to equation 6

$Z'_{M_{AI}}$ = The same but in accordance to equation.

$Z_{M_{AII}}$ = the impedance measured by distance relay R_{AII} in accordance to equation. 8

$Z'_{M_{AII}}$ = The same but in accordance to equation 9

From sequence diagram we have

$$V_{R_A} = m\Big[Z_{1_I} I_{1_{AI}} + Z_{2_I} I_{2_{AI}} + Z_{om}(I_{o_{AI}} + I_{o_{AII}}) + I_{o_{AI}}(Z_{oo} - Z_{om}) \Big] \quad \text{----(2)}$$

$$= m\Big[Z_{1_I} I_{1_{AI}} + Z_{2_I} I_{2_{AI}} + \cancel{Z_{om} I_{o_{AI}}} + Z_{om} I_{o_{AII}} + Z_{oo} I_{o_{AI}} - \cancel{Z_{om} I_{o_{AI}}} \Big]$$

$$= m\Big[Z_{1_I} I_{1_{AI}} + Z_{2_I} I_{2_{AI}} + Z_{om} I_{o_{AII}} + Z_{oo} I_{o_{AI}} \Big]$$

If $Z_{1_I} = Z_{2_{II}}$

and $(I_{1_{AI}} + I_{2_{AI}} + I_{o_{AI}}) = I_{R_A}$ ----(3)

= fault current in conductor R

It follows.:

$$V_{R_A} = m \left[Z_{1_I} I_{1_{A_I}} + Z_{2_I} . I_{2_{AI}} + Z_{om} \frac{I_{M_{AII}}}{3} + Z_{oo} . \frac{I_{M_{AI}}}{3} \right]$$

Adding and substracting $I_{o_{AI}} . Z_{1_I}$ we get

$$V_{R_A} = m \left[Z_{1_I} I_{1_{AI}} + Z_{2_I} . I_{2_{AI}} + I_{o_{AI}} . Z_{1_I} - I_{o_{AI}} . Z_{1_I} + Z_{om} . \frac{I_{M_{AII}}}{3} + Z_{oo} \frac{I_{M_{AI}}}{3} \right]$$

$$V_{R_A} = m \left[Z_{1_I} (I_{1_{AI}} + I_{2_{AI}} + I_{o_{AI}}) - \frac{Z_{1_I}}{3} \times I_{M_{AI}} + \frac{Z_{oo}}{3} . I_{M_{AI}} + \frac{Z_{om}}{3} I_{M_{AII}} \right] \text{---(4)}$$

IF

$$K_1 = \frac{Z_{oo} - Z_{1_I}}{3 \; Z_{1_I}} \quad \text{and} \quad K_2 = \frac{Z_{om}}{3 \; Z_{1_I}}$$

Therefore

$$Z_{oo} = Z_{1_I} \left[3 K_1 + 1 \right] \quad \text{and} \quad Z_{om} = 3 \; Z_{1_I} . K_2$$

Substituting the values of Z_{oo} and Z_{om} in equality (4) we get.

$$V_{R_A} = m\left[Z_{1_I}.I_{R_{AI}} - \frac{Z_{1_I}}{3}.I_{M_{A_I}} + K_2 3.Z_{1_I}.\frac{I_{M_{AII}}}{3} + \frac{I_{M_{AI}}}{3}\left(Z_{1_I}3K_1 + Z_{1_I}\right)\right]$$

Therefore,

$$V_{R_A} = m\,Z_{1_I}\left[I_{R_{AI}} + K_2 I_{M_{AII}} + K_1 . I_{M_{AI}}\right]$$

Therefore distance proportional impedance of the faulted line at station A is

$$m\,Z_{1_I} = \frac{V_{R_A}}{\left[I_{R_{AI}} + K_1 . I_{M_{AI}} + K_2 I_{M_{AII}}\right]} \quad \text{------}(5)$$

It is evident from equation (5) that for an earthfault on one system of a double line, the distance proportional to fault impedance is measured accurately, if the voltage circuit of the impedance-measuring relay receives the faulted-line-to -earth voltage and the current-circuit receivesthe vector sum of the faulted conductor and of that portion of the residual current of the faulted system 1 determined by factor K_1 plus that portion of the residual current of the sound parallel system 2 determined by factor K_2.

However in conventional distance relay, the voltage circuit receives the faulted-line-to-earth voltage and current circuit receives only the vectorial sum of the fault current $I_{R_{AI}}$ and part of the residual current $K_1 I_{M_{AI}}$ of the faulted line. They lack in the residual current $K_2 I_{M_{AII}}$ of the sound system in current circuit. Therefore the impedance $Z_{M_{AI}}$ measured by a convention distance relay with an earth fault on one system of double circuit line is given by

$$Z_{M_{AI}} = \left| mZ_{1_I} \right| \times \frac{\left| I_{R_{AI}} + K_1 I_{M_{AI}} + K_2 I_{M_{AII}} \right|}{\left| I_{R_{AI}} + K_1 I_{M_{AI}} \right|} \quad \text{---(6)}$$

The equation (6) differ from equation (5) as the term $K_2 I_{M_{AII}}$ is lacking in the demominator.

The relative error in distance measuring is then

$$\triangle Z_{M_{AI}} = \frac{\left| Z_{M_{AI}} \right| - \left| m\, Z_{1_I} \right|}{\left| m\, Z_{1_I} \right|}$$

$$= \frac{\left| I_{R_{AI}} + K_1 I_{M_{AI}} + K_2 I_{M_{AII}} \right|}{\left| I_{R_{AI}} + K_1 I_{M_{AI}} \right|} - 1 \quad \text{---(7)}$$

Now examining the condition when neutrals at both the ends of the double circuit line are earthed and an earthfault occurs near station A. The residual current ($I_{M_{AII}} = 3I_{o_{AII}}$) in sound-system becomes negative and current $I_{o_{AII}}$ flows against the direction shown in Fig, 8(a) . Therefore the fraction of equation (7) becomes negative and the error negative. The conventional distance relay measures impedance values too low for earthfaults near station A. With earth-faults located near the station B, the residual current $I_{o_{AII}}$ in sound system changes the direction and the error becomes positive and is maximum when $m = 1$. The measured impedance value is then too high and the relay is under-reaching. When the neutral at station A is only earthed the current $I_{o_{AII}}$ flows in the direction shown in Fig. 8(a) independent of the location of the earthfault. Then the error is always positive and becomes considerably high for $m \rightarrow 1$ (approx. 40%)

The distance relay R_{AII} of the sound system II in station A measures the fault impedance of the earth-fault on an system I as follows :

$$Z_{M_{AII}} = \left| m Z_{1_I} \right| \times \frac{\left| I_{R_{AI}} + K_1 I_{M_{AI}} + K_2 I_{M_{AII}} \right|}{\left| I_{R_{AII}} + K_1 I_{M_{AII}} \right|} \qquad \text{----(8)}$$

When it is of conventional type.

But if in the current path of this distance relay R_{AII} , the proportion $K_2 I_{M_{AI}}$ of the residual current of the faulted line is also introduced, then the impedance measured by this relay is

$$Z'_{M_{AII}} = \left| m\, Z_{1_{I}} \right| \times \frac{\left| I_{R_{AII}} + K\; I_{M_{AI}} + K_2\, I_{M_{AII}} \right|}{\left| I_{R_{AII}} + K_1\, I_{M_{AII}} + K_2\, I_{M_{AI}} \right|} \quad \text{---}(9)$$

When the transformer neutral at station A only is earthed and an earthfault occurs near station A on line I then the residual current $I_{M_{AI}}$ becomes very high.

Therefore $Z'_{M_{AII}} < Z_{M_{AII}}$

This decrease of $Z_{M_{AII}}$ by introducing the part of the residual current of the faulted line $K_2 I_{M_{AI}}$ into the current path of the distance relay R_{AII} may in some cases intiate an undesired tripping. Thus operation of the relay is unselective and effords therefore special measures for elimination.

CHAPTER 2.

STATIC PROTECTION RELAYS

2.1. DEVELOPMENT :

As author's investigations are mainly concerned with static relays and circuits it is felt proper to review precisely the development of these static devices. In static relays, the general trend is to use static circuits for the comparison and measurement of input signals and to have only a slave relay to initiate tripping.

There are two main types of static relays that have received attention in protective relay application

(a) Relays using thermionic valves.

(b) Relays using transistors.

2.1.1. RELAYS USING THERMIONIC VALVES:

Rolf Wideroe(6) was the first to introduce electronics in protective relaying using thyratron tubes. The property of the thyratrons whereby below a certain value of voltage applied to its grid, it does not fire, but once the voltage was raised above a given threshold, it does fire, led to the investigation of a complete family of relays. The relays such as undervoltage, overcurrent, power directional and distance of both high speed and low speed varities, all used input circuits consisting of transformers, metal rectifiers and linear R, L, C circuit components. In these circuits the various functions of system voltage, and if required, system current were summated and compared, the resultant always being a single voltage for application to the thyratron grid.

The first relay using thermionic valves was described by Macpherson, Warrington and McConnel(7) and was applied for distance protection. The basic principle was to compare line voltage with line current at the moment of line-voltage maximum. This pulse type relay using three basic elements gave 'Mho' type characteristics The elements used were:

(i) a pulsing circuit.
(ii) a measuring circuit.
(iii) a tube circuit.

The function of the pulsing circuit was to generate a pulse at the moment of line-voltage maximum. The pulse was used to overcome a large grid bias and permit a tube to conduct. The function of the measuring circuit was to compare the line voltage with the line current. The tube circuit was the sensitive element which was responsive to signals from both the measuring circuit and pulsing circuit. The tube circuit also initiates the tripping signal to the circuit breaker when the impedance being measured falls below that for which the relay has been set to operate.

The overall speed of operation was claimed to be 1½ cycles. Other advantages claimed were, negligible burdens on C.T's and V.T.'s and freedom from mechanical instability.

In 1949, J.J. Loving(9) in his paper laid some principles for the electronic protection of systems in which mode of operation of relays was same irrespective of the type of relaying employed e.g. distance, directional overcurrent etc. This general method is illustrated in Fig. 9(a). Most of his polyphase circuits had infact seperate current and voltage responsive circuits, pulse forming, fault detecting and functional elements for each phase and the only common circuits for the three phases were the impulse circuits which responded to the final signal.

Pulses are formed from one of the system quantities, in this case from each of the three C.T's. These pulses are first fed to detector circuit, the purpose of which was to detect the fault and then to functional elements e.g. directional elements, with control provided by voltage signals. If the functional elements detected a fault within the protected section, then the pulses passed on to operate an impulse circuit and then to circuit breaker trip coil. Although Loving's investigations covered a very wide field of protection but the circuits have never been used in actual relaying applications due to disadvantages associated with electronic circuits utilising thermoinic valves. His was the last attempt to use normal electronic techniques with thermionic valves.

In 1954, Bergseth(10) published a paper on direct-phase comparison distance relay using a diode co-incidence circuit, while in the same year Kennedy(12) described an electronic carrier relaying scheme using no electromagnetic relays at all, even tripping being performed by the use of a heavy duty thyratron . These were the final developments using thermionic values. In general, electronic relays using thermionic tubes have not met with much favour in the electricity supply industry because of their requirements in heater and anode supplies. Junction transistors overcome the limitations of thermionic valves so far as H.T. and heater requirements are concerned. No heater supplies are needed and the H.T. demands are modest with regard to both voltage level and power.

2.1.2. TRANSISTORS IN RELAYING

The applications of transistors in relaying have been confined to following three categories:

(a) Use of transistors as an amplifying element with the main object of increasing the sensitivity of an electromagnetic relay.

(b) Direct application of transistors to relaying circuits for which electronics is already a standard practice e.g. phase comparison carrier.

(c) The use of transistors or group of transistors to perform a particular function which gives the whole or part of the characteristics of a static relay.

The potentialities of the Junction transistors were investigated for certain protective-gear applications

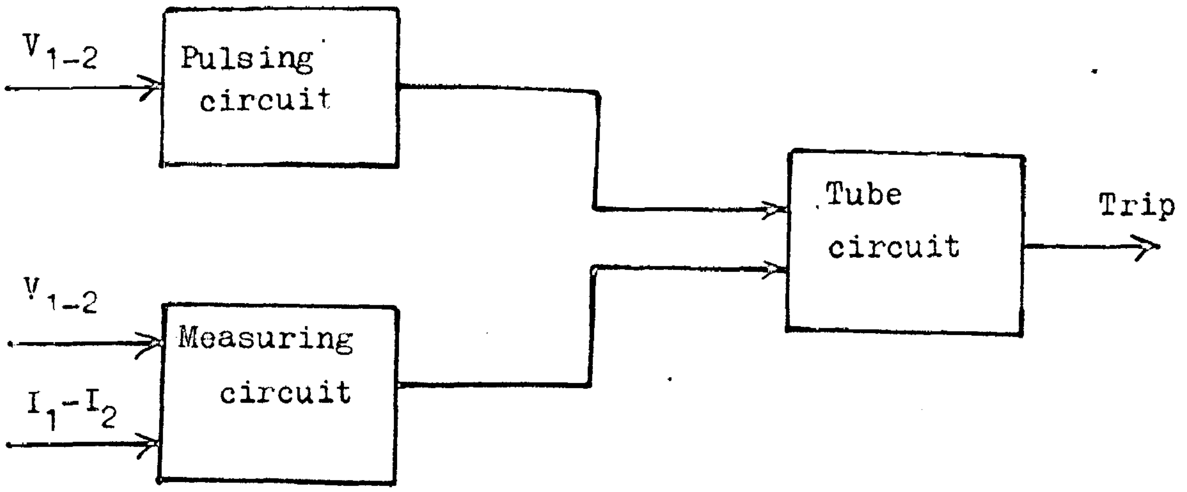


Fig. 9(a)

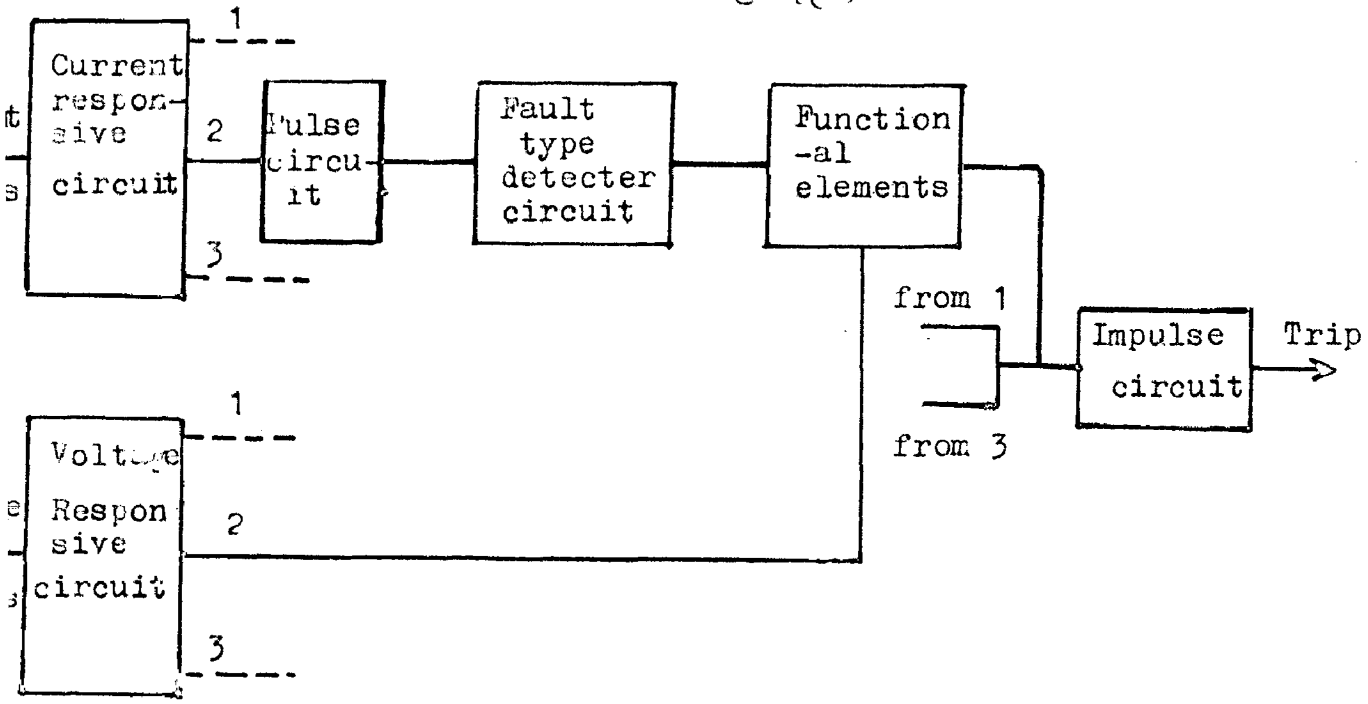


Fig. 9(b)

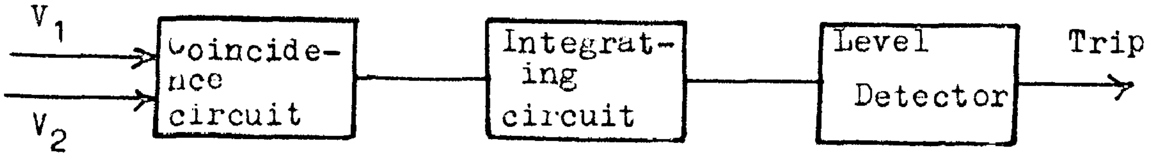


Fig. 9(c)

at Manchester College of Technology in the year 1954. Wedepohl started work on distance relays and the first transistor distance relay using direct phase comparison was later published(11,14). This relay called the dual comparator 'Mho' type relay is shown in Fig. 9(c). V_1 and V_2, the two derived voltage inputs from the system fault voltage and current were applied to a coincidence circuit.

The output of the coincidence circuit was a voltage block lasting for duration of coincidence. The output of the coincidence circuit was applied to an integrating circuit which charged up linearly over the period during which output was present and reset to zero potential when the output dis-appeared. The magnitude of the voltage attained by the integrating circuit was thus the function of the angular displacement ϕ between V_1 and V_2 and would be maximum for $\phi = 0$ and zero for $\phi = 180°$. A level detector circuit followed the integration circuit and was adjusted so that a tripping output was corresponding to 90° phase displacement between V_1 and V_2. The tendency to over-reach on d.c. offsets was solved by using a dual comparator where the comparator input quantities were (i) V_1 and V_2 and (ii) $-V_1$ and $-V_2$.

In 1959 Adamson and Talkhan published a paper(13 replacing thermionic valves completely with Junction transistors in phase comparison carrier protection. Their results also include findings on the extensive life tests carried out on transistors.

These and other developments in transistor applications to protective relaying have led to the possibility of having high speed, reliability, accuracy and robustness together. Progress and development in transistors is rapidly bringing to their rating and power into a situation where they will be of real practical value in the design and development of new protective -gear systems and relays.

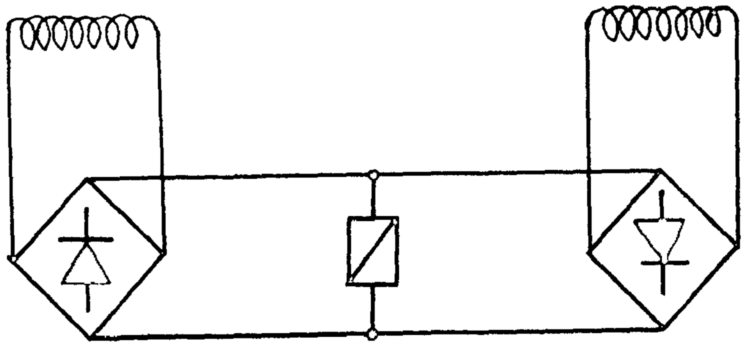
Transistorised relays are, however, facing severe competition from rectifier bridge comparator type relays because of their excellent characteristics.

2.2. RECTIFIER BRIDGE COMPARATORS:

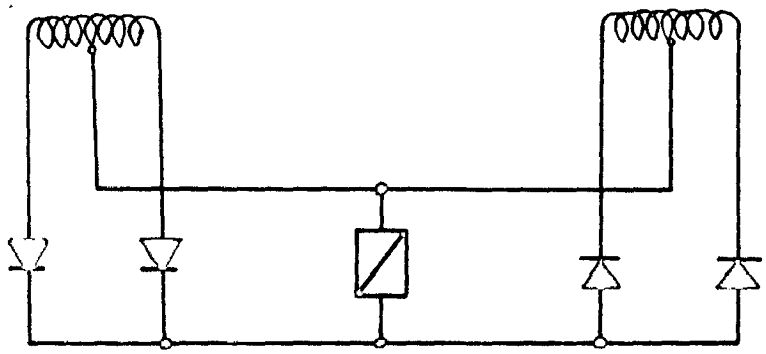
Rectifier bridge comparators are producing great amount of excitation amongst protection engineers to-day. It is increasingly being used as a static amplitude comparator in distance type, current balance and differential relays.

The rectifier bridge comparator was first applied to protective relaying in Norway and Germany and was later taken up in a commercial form by Germany(15). It is now in wide use commercially in the U.K., U.S.A. and continental Europe(8,16).

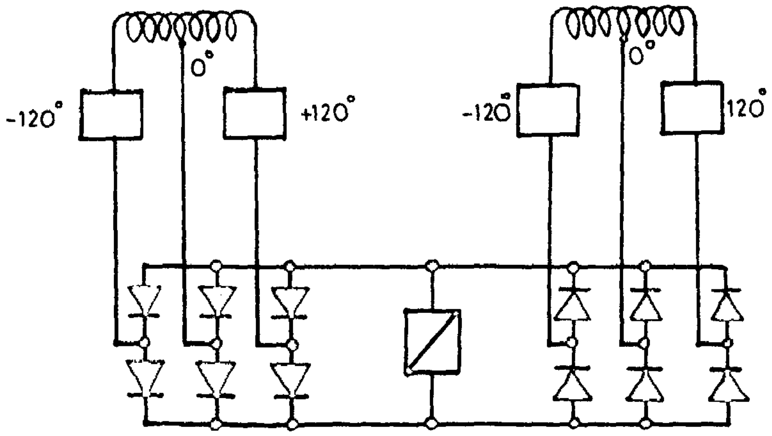
The rectifiers are generally used as current convertors i.e. the current flow is enforced through them. The three main types of rectifier bridge comparator circuits are shown in fig. 10. In present-day



(a) GRAETZ CONNECTION



(b) MID POINT CONNECTION



(c) SPLIT PHASE CONNECTION

FIG. 10 RECTIFIER BRIDGE COMPARATOR-DIFFERENT CONNECTIONS practice use is made of rectifiers in Graetz connection. The split phase connection is used only where a smooth d.c. output is needed, without introducing inductive-capacitive smoothing filters. The mid-point connection is rarely employed.

2.3. MOVING COIL RELAYS:

With definite advantages claimed for high speed protections, there has been a trend to eliminate large magnetic circuits and to introduce high speed relays with simpler movement, which led to introduction of moving coil relay(21).

The polarised moving coil system is based on the inter-action of the polarised flux of a permanent magnet with the magnetic flux in the moving coil passing a direct current. The relay has a loud speaker type, movement and is wound with two coils. One coil is supplied with full wave rectified current tending to move the element in the operating direction while the second coil is energised with a full wave rectified current tending to restrain the element.

CHAPTER 3.

BASIC AMPLITUDE COMPARATOR USING RECTIFIER BRIDGE

3.1. BASIC COMPARATOR

A comparator works on the principle of comparing its vector inputs and provides an output signal depending upon their relationship (magnitude or phase or a combination of both). The inputs to comparators are derived from the system usually by current or voltage transducers with suitable modifying circuitry to obtain a required operating characteristic. The most general case is where two system quantities 'p' and 'q' are each presented after linear transformation to both inputs of a comparator. The two inputs to the comparator are then

$$S_1 = K_1p + K_2q$$

$$S_2 = K_3p + K_4q$$

where p and q may be current or voltage.

There are two types of comparators:

(a) Amplitude comparators.

(b) Phases comparators.

Amplitude comparators compare the scaler magnitude of the two vector imputs. These operate when the modulus of one vector input is greater than that of the other and restrain when it is less.

On the other hand phase comparators depend for their operation on the phase difference between the inputs and operate when the angle θ between the vectors lies between certain limits say θ_c and θ'_c and restrain over the remaining portion of the full 360°.

These two relations for two types of comparators can be expressed mathematically by putting

$$\frac{\bar{S}_1}{\bar{S}_2} = \rho e^{j\theta}, \qquad \bar{\rho} = \text{plane}$$

Thus for,

Amplitude comparison

$$\frac{|S_1|}{|S_2|} = \rho$$

While for phase comparison

$$\arg\left(\frac{\bar{S}_1}{\bar{S}_2}\right) = \theta$$

By choosing particular values for ρ and θ, marginal condition for operation is determined for a particular type of comparator.

For example,

Operate for $\rho > \rho_0$ and restrain when $\rho < \rho_0$ for amplitude comparator.

A rectifier bridge comparator has ρ equal to unity.

For phase comparator

operate for $\theta'_o < \theta < \theta'_c$

Restrain for $\theta'_c < \theta < \theta_c$

In the complex ρ plane Fig 11

defines a particular circle while θ_c and θ'_c define particular radii dividing the operating region from non-operating.

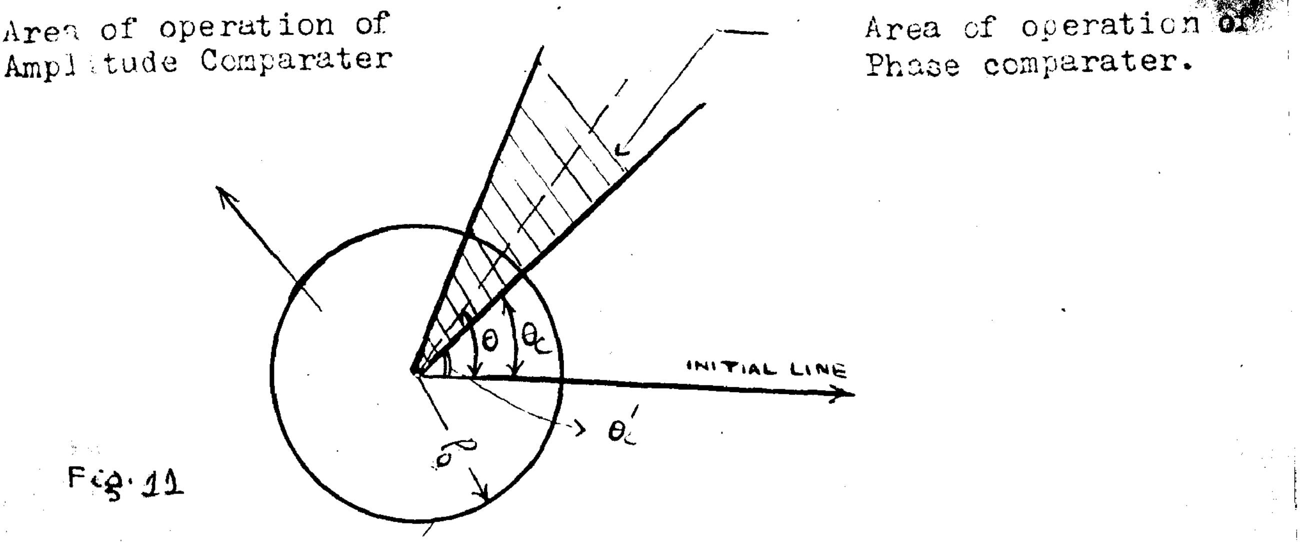


Fig. 11

3.2. COMPARATOR DEVICES:

Amplitude as well as phase comparators both can be designed using rectifier bridges . However amplitude comparator has exclusively been realised using rectifier bridges only where as phase comparators can be designed by using junction transistors also. [8]

3.3. RECTIFIER ELEMENT:

Considerable divergence of opinion exists with regard to the best types of rectifier to be used for these comparators. The four main possibilities being selinium, silicon, germanium and copper oxide. Selinium has had the widest application in U.K. and is prefered on account of its well definate threshold on I-V characteristics, a tendency to retain its initial character with aging and a good over load performance. In silicon it is claimed, that such rectifiers are very satisfactory in relaying applications.

Some German opinion favours germanium largely on the ground that such rectifiers are much less susceptible to failure because of moisture than selinium or copper oxide. It has also been suggested that selinium rectifiers deteriorate in fluorscent lighting where germanium and copper oxide do not.

3.4. RECTIFIER BRIDGE AMPLITUDE COMPARATOR:

The author has designed a balanced current relay for the protection of parallel feeders by using a static rectifier bridge comparator and a sensitive d.c. moving coil relay serving as indicator.

Basically the comparator consists of two full wave rectifiers connected in series aiding as shown in Fig. 12(a) a polarised moving coil relay being connected across the two rectifiers. The relay has a single coil and comparison between system quantities is affected in a d.c. differential circuit formed by the two rectifiers. Thus the measurement is made by null method, the d.c. relay indicating only the deviation from the measuring point determined by the constants of the bridge.

3.4.1. BEHAVIOUR UNDER IDEAL CONDITIONS:

It is assumed that two inputs to the comparator are from ideal current sources i.e. the impedance of the two sources could be considered as infinity. In practice, however no such ideal current source exists and any source is basically a voltage source. Where the source impedance is very large, however, it can for all practical purposes be considered as an ideal current source, but difficulty arises

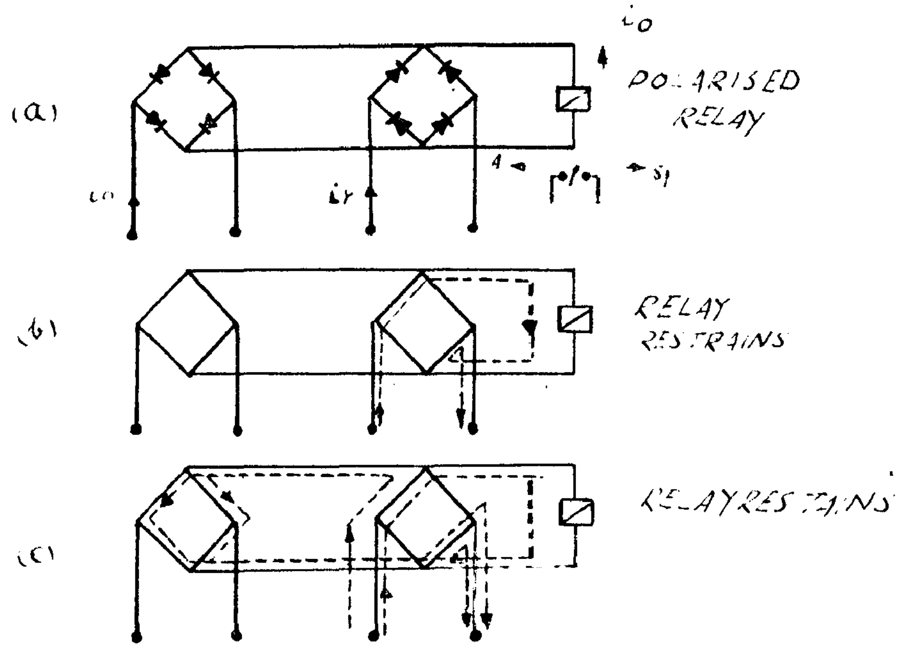
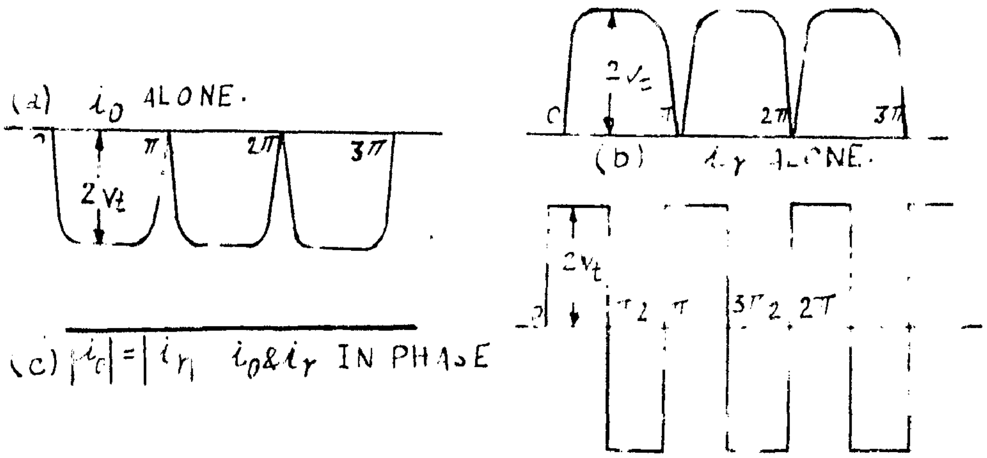


Fig 12



(a) i_0 ALONE.

(b) i_r ALONE.

(c) $|i_0|=|i_r|$ i_0 & i_r IN PHASE

(d) $|i_0|=|i_r|$ i_0 & i_r OUT OF PHASE.

FIG 13 MOVING COIL RELAY VOLTAGE WAVE FORMS.

where this impedance cannot be made large due to other circuit limitations.

3.4.2. OPERATION UNDER IDEAL CONDITIONS:

Where the two inputs are from ideal current sources, the operation of the measuring rectifiers is as follows :

Normally the restraining current preponderates and current flows in the winding of the polarised moving coil relay in the blocking direction. If only small value of current i_r is flowing through bridge 2, the whole of this current will flow through the relay as shown in Fig. 12(b) and causes a voltage drop - V across the relay. This voltage drop serves as a forward bias for rectifier bridge 1 . When i_r is increased further, the voltage drop across the relay rises to - 2 V_t, the threshold voltage of bridge 1 and the rectifier bridge 1 will conduct. Thereafter due to non-linear characteristic of the rectifier any unbalance current exceeding 2 to 3 times the operating value of the relay flows through the bridge 1 as shown in Fig. 12(c) thus preventing the relay from overloading.

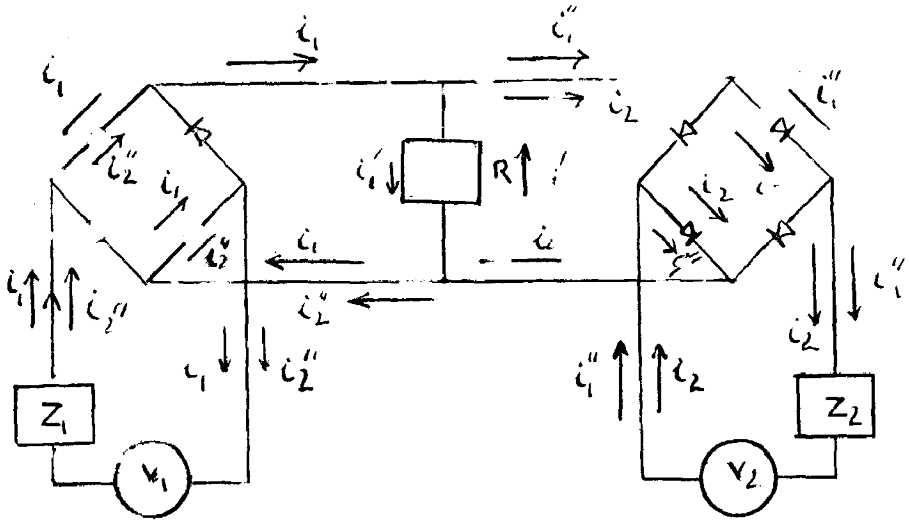
When both bridges are energised simultaneously i.e. when both i_r and i_o are present and in phase, the comparison of system quantities is affected in the d.c. differential circuit formed by the two bridges and complete relay arrangement is actually sensitive to small difference between i_o and i_r. If both the currents are equal, independent of their absolute values, the relay D_r carries no current, the rectifiers work on short circuit and take practically no power. If the currents are unequal, the excess current flows through the relay D_r, the direction depending upon which current is greater i.e. the polarised relay makes contact on one side or the other side. If $i_o > i_r$, the contact shall remain in its tripping position A - on the other hand if $i_r > i_o$, the contact shall open and block the tripping (S_p). If the difference between i_o and i_r is very great, the excess current after exceeding the threshold value bypasses the relay. Accordingly at very high unbalance currents, the rectifiers work practically short circuited and are therefore stressed only by the voltage due to their internal resistance. This bridge circuit therefore gives full sensitivity of operation, protects the rectifiers against voltage stress and also the moving coil relay against overloading.

When i_o and i_r are not inphase the voltage across the relay will be a square wave of double the fundamental frequency and if the two currents are equal in magnitude the relay voltage is a soquare wave with equal positive and negative components as shown in Fig. 13(d) giving zero average voltage over one half cycle of the fundamental voltage wave; the polarised relay operating on the average input to its terminals therefore develops no torque, since the average voltage over one cycle of the positive and negative components of this square wave is each equal to V_t. Here it has been assumed that the voltage developed across the polarised relay by each current input individually with the other bridge rectifier dis-connected is large compared to 2 V_t.

4.3. BEHAVIOUR UNDER CONDITIONS WHERE THE INPUT SOURCES ARE NOT IDEAL CURRENT SOURCES:

SHUNT EFFECT BETWEEN THE TWO SOURCES:

The behaviour of bridge comparator under such conditions is shown in Fig. 14 . Untill the voltage across t



V_1, V_2 = [illegible]

R = Moving Coil Relay of impedance R.

Z_1, Z_2 = Internal Impedances of Voltage Sources.

i'_1 = Relay Current fed from V_1.

i''_1 = Shunt Current fed from V_1.

i'_2 = Relay Current fed from V_2.

i'_2 - Shunt current fed from V_2.

$$(i'_1 + i'_2) = i_1$$

$$(i'_2 + i''_2) = i_2$$

Fig 14 Rectifier Bridge Comparator with Voltage Sources relay 'R' reaches the threshold voltage to open the rectifiers on either side, the current from each side in each half cycle gets a shunt path through the finite impedance of the other source. When i_2 is flowing in the direction marked, two rectifiers are conducting and the shunt current i_d flows through these rectifiers and the source V_2. When V_2 changes its polarity, the other two rectifiers start conducting with the result that shunt current also has to reverse in polarity in order to follow the low resistance parth provided by the conducting rectifiers.

The shunt current is therefore a pulsating current and the wave shape will be distorted when the two signal currents are out of phase. When they are inphase, the shunt current will be approximately sinusoidal. The shunt effect from the other end is similar to the first one considered. There is thus a mutual effect between the two voltage sources. This tends to reduce the sensitivity of the relay at the operating point because this mutual effect is predominant when the relay is just at the verge of operation as it is only then the voltage across the relay is very low. It has been shown mathematically by Dr. T.S.M.Rao(19) that mutual effect is a minimum when the two voltage sources have equal interval voltages.

CHAPTER 4.

STATIC SCHEMES FOR PARALLEL FEEDER PROTECTION

4.1. INTRODUCTION:

Two static schemes have already been put forward by various authors for the protection of parallel feeders. In one of the schemes Russian engineers(20) have designed a semiconductor balance-current relay giving characteristics similar to their I.T.B-201 electromagnetic balance-current relay, second scheme has been put forward by British engineers(21) for the protection of any number of feeder using a moving coil relay for each protected feeder. Both these schemes are briefly reviewed here.

4.1.1. STATIC SCHEME I USING SEMICONDUCTOR BALANCE-CURRENT RELAY :

The fundamental circuit diagram of the relay is shown in Fig. 15 . The operating transformer ($T_{r.op}$) has two secondary windings W_{2op} and W_{3op}, and passes the current of the line to be protected. The current of the parallel line passes through the primary winding of the restraint transformer ($T_{r.Res}$) which has one secondary winding. The holding transformer ($T_{r.H}$) is supplied from a voltage transformer on the bus-bars of the protected section. The actuating relay is a polarised relay with operating and restraining windings.

The emf from the secondary winding W_{2op} of the operating transformer is fed to rectifier bridge B_1 and smoothened by the capacitance 'C_1' acts on the operating winding of the actuating device. The emf from the winding

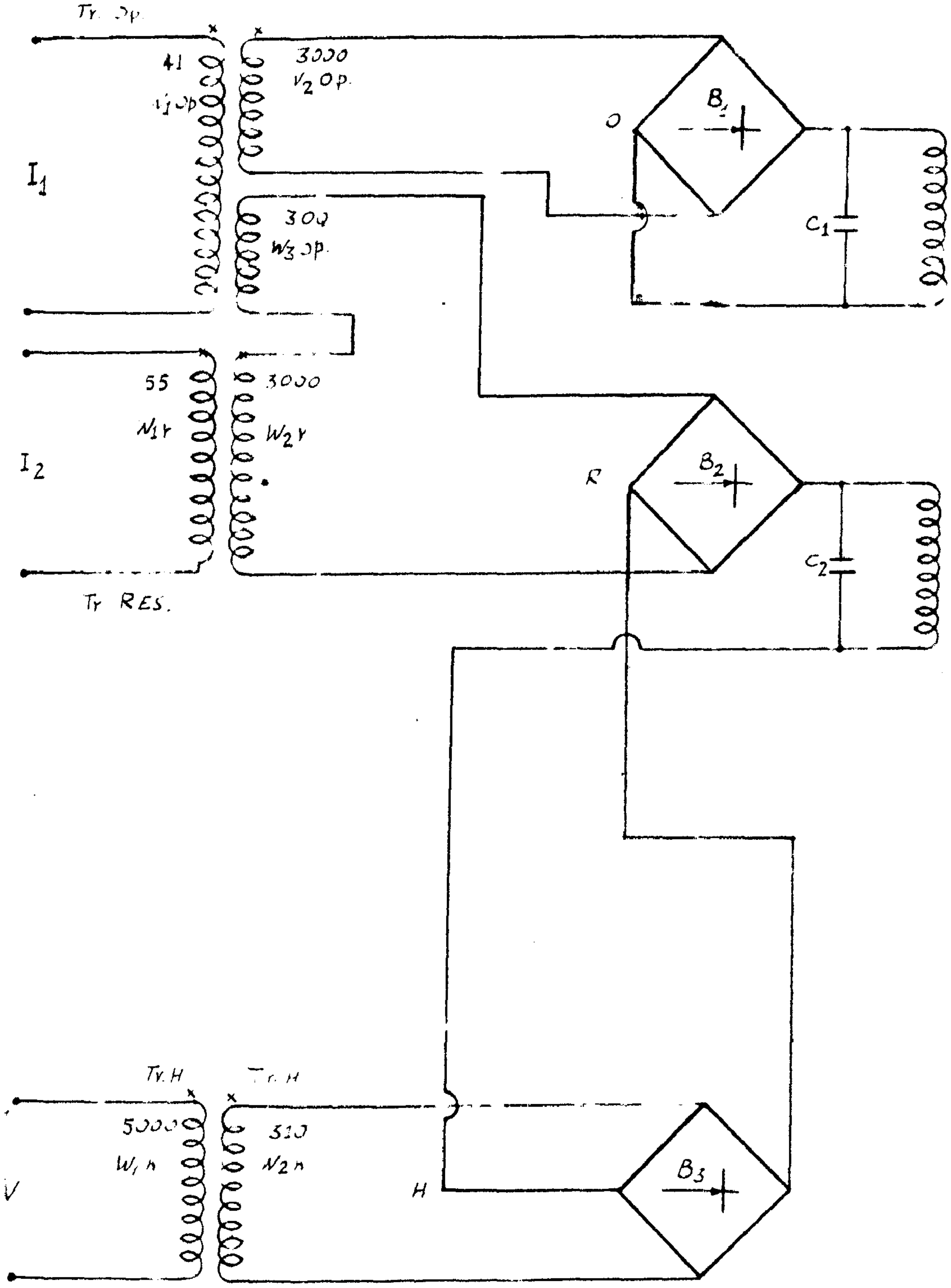


Fig. 15 FUNDAMENTAL CIRCUIT DIAGRAM OF THE RELAY.

W_{3op} of the operating transformer is added to or substrac. from, the secondary emf of the restraint transformer depending upon the phase relationship of the currents in the protected and parallel line. Their combined output is fed to the second rectifier bridge B_2. The third rectifier bridge B_3 is supplied by the secondary voltage of the holding transformer.

Rectifier bridges B_2 and B_3 are connected in series and their output acts on the restraint winding of the actuating relay.

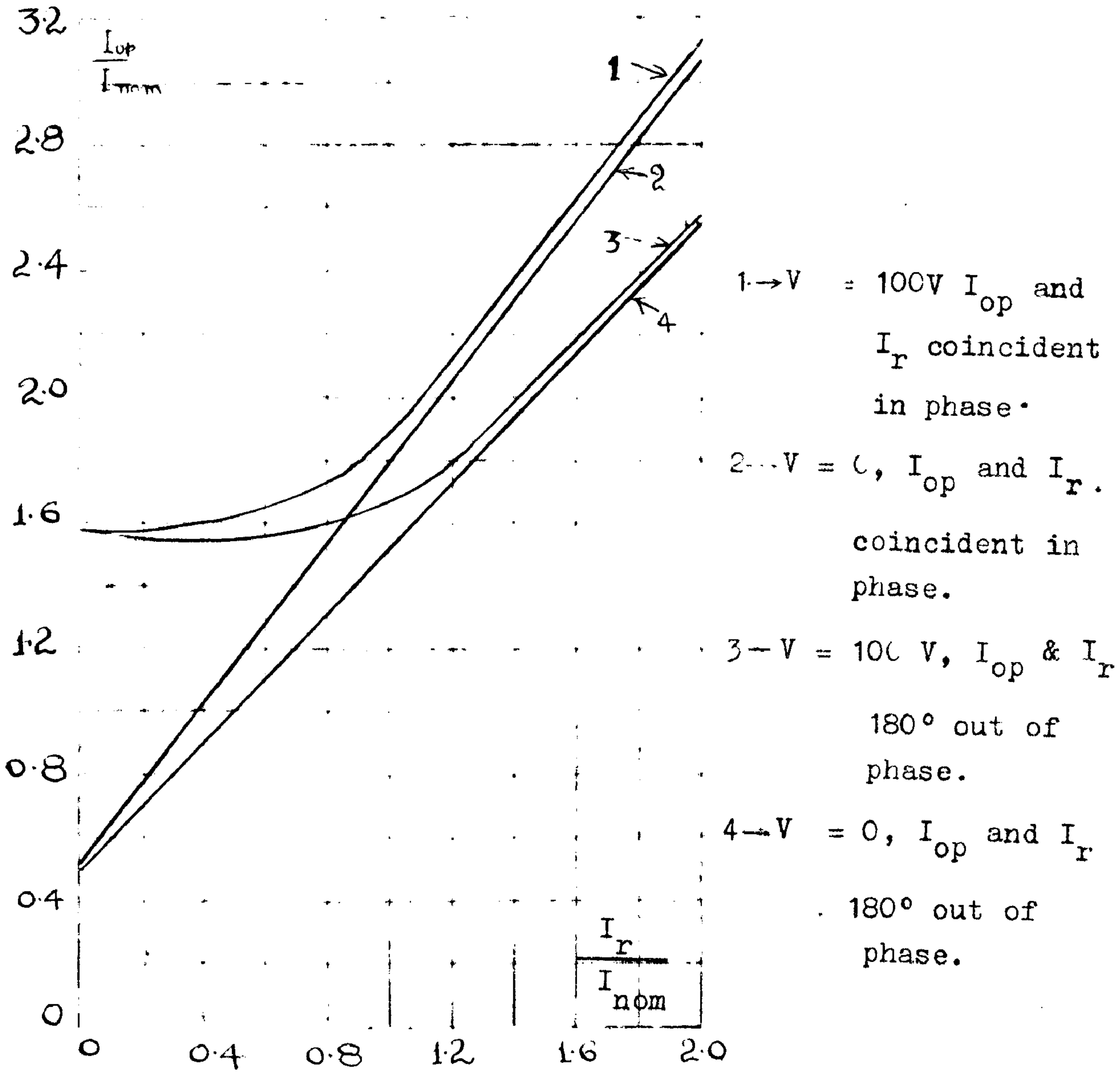
The summation of the restraint, holding and operating ampereturns takes place on the actuating device. The turns ratio of the auxiliary transformers are such that the relay does not operate if the currents in the protected and parallel lines are equal in magnitude, which is the normal condition of operation of the parallel lines.

With a short circuit on the protected line

$I_{op} > I_r$ so that

$(A.T)_{op} > (A.T)_{rest}$.

and the relay operates to trip the faulty line. Junction diodes are used for rectifier bridges. The performance characteristic of the relay are shown in Fig. 16 . The characteristics of this relay are claimed to be analogous to those of Russian I.T.B. -201 electro-magnetic balanced current relay.



1→V = 100V I_{op} and I_r coincident in phase.

2→V = 0, I_{op} and I_r coincident in phase.

3→V = 100 V, I_{op} & I_r 180° out of phase.

4→V = 0, I_{op} and I_r 180° out of phase.

Fig. 16 (Characteristics $I_{op} = f(I_r)$)

4.1.2. SECOND STATIC SCHEME:

This scheme is based on the comparison of current in each individual feeder with the average current of the whole group of feeders.

Such comparison at sending end in a group of parallel feeders indicates that

(a) the current values in each feeder will be nearly equal under normal load or through fault conditions.

(b) With faults interval to the protected zone, the current in the faulty feeder will always exceed the average current for the whole group.

At Pure Receiving End.

(c) With faults internal to the protected zone the average current is zero and is exceeded by the current in each feeder in the group.

(d) The direction of flow of fault current is away from the local bushbars in the case of faulty feeder only.

It is apparent from the above facts that a differential relay whose operating force is proportional to the current in the feeder, and the restraint force is proportional to the average current of the group can be used at sending end to provide the necessary discrimination of the faulty feeder. However at pure receiving end reliance is placed upon directional relay. To avoid false tripping

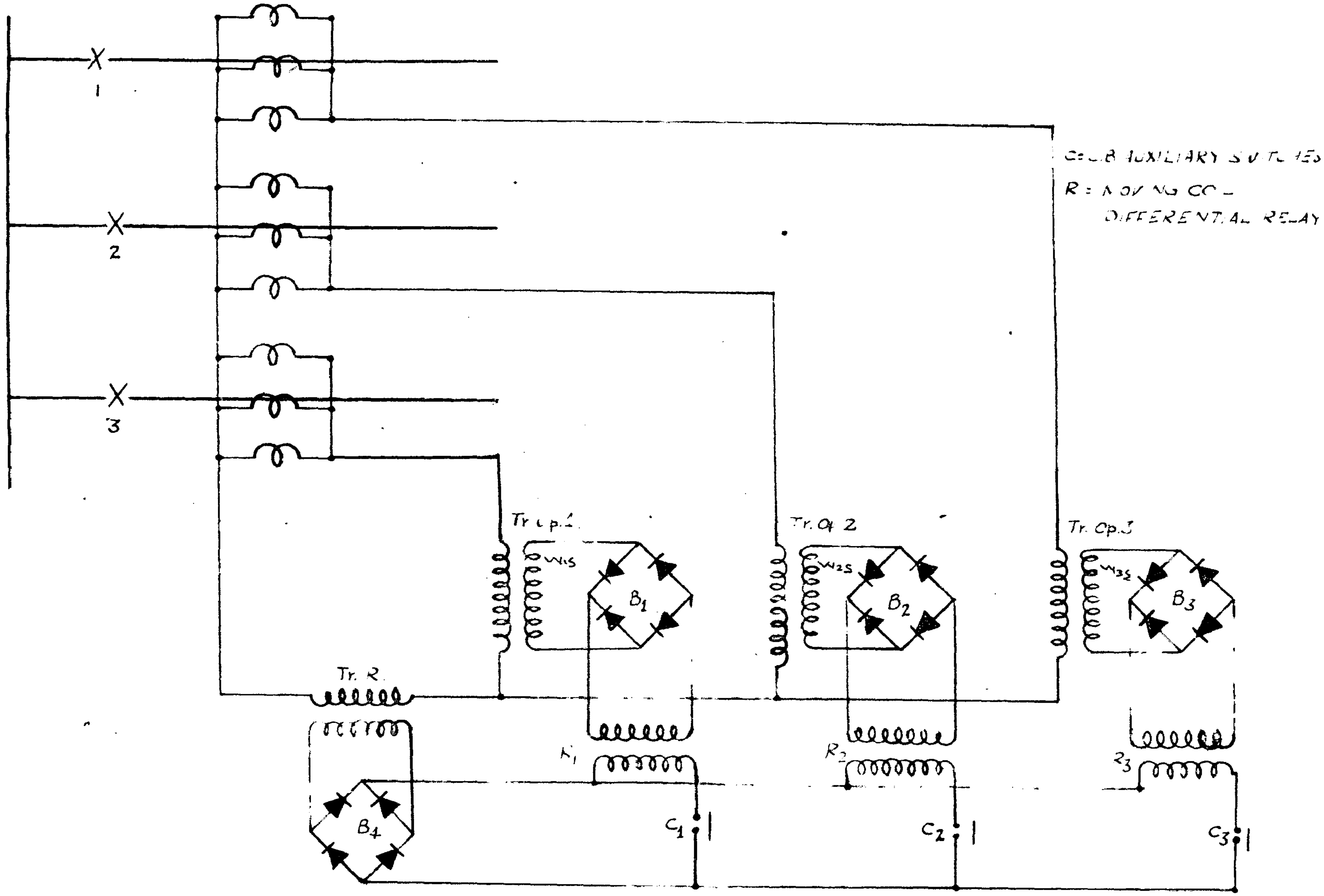


Fig. 17 CURRENT CONNECTIONS FOR EARTH-FAULT DIFFERENTIAL PROTECTION OF THREE PARALLEL FEEDERS.

it is essential that differential and directional relays be interlocked and that directional relay should operate only during fault conditions.

EARTH-FAULT SCHEME:

The circuit diagram of the scheme which uses the above principle, for providing earth-fault protection is shown in Fig. 17.

The input circuits are auxiliary current transformer circuits. The current of each protected feeder passes through primary winding of their respective operating transformers (T_{rop_1}, T_{rop_2}, T_{rop_3}) The currents from each of the secondary windings (W_1S, W_2S and W_3S) of the operating transformers are fed to their respective rectifier bridge B_1, B_2 and B_3 and act on the operating windings of the moving coil relays R_1, R_2 and R_3 respectively. The primary winding of the restraining transformer T_{rR} is supplied by the current of the whole group of parallel feeders. The turns ratio of the restraining transformer is such, that its secondary winding supplies to rectifier bridge B_4, the average current of the whole group of feeders. The output of the rectifier B_4 supplies the restraining coils of the moving coil relays which are connected in parallel. In order that small discrepancies between feeder currents shall not cause instability the effective restraint-coil mmf is 20% greater than the operating coil mmf. This margin is maintained constant with varying number of feeders in service by use of circuit breaker auxiliary switches C_1, C_2, C_3etc.or other means to vary the number of restraint coils connected in parallel.

The summation of the operating and restraining mmf for each feeder takes place in its respective moving coil relay. With faults internal to the feeder group

$$I_{op} > I_{an} \quad \text{so that}$$

$$(A.T.)_{op} > (A.T.)_{av}$$

and that particular relay belonging to the faulty feeder operates to trip the faulty feeder.

The operating characteristics of a typical protective scheme of this type for faults in various positions on one of a pair of feeders are shown in Fig. 18 .

PHASE AND EARTH FAULT PROTECTION:

The scheme for phase faults is similar to that described above except that each phase is balanced independently and has seperate relay elements . As the differential relays must now carry load currents they will tend to close their contacts during normal switching operations on the feeders. To prevent false tripping of these relays due to load current additional differential windings supplied from the main voltage transformers are included. The differential relays are set below full load current (approx. 40%), when a fault occurs , the voltage collapses and the current circuits with their low setting are left in control.

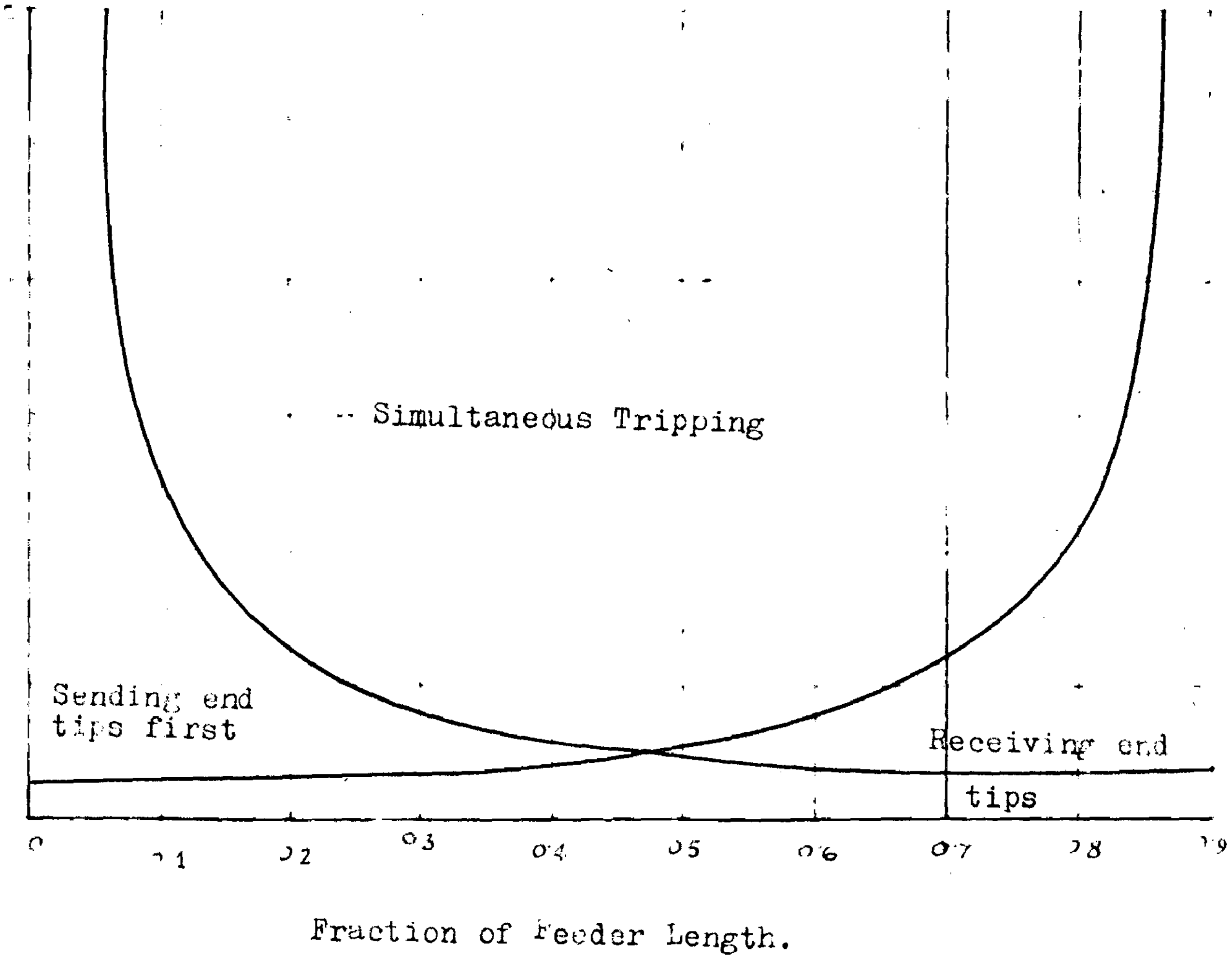


Fig. 18 Setting curves for high speed differential protection for parallel feeders.

For receiving end, same scheme is used except that directional relay is added. The current coil of each directional relay is connected in series with the primary windings of operating transformers.

CHAPTER 5.

RECTIFIER BRIDGE TYPE BALANCE CURRENT PROTECTION

5.1. PRINCIPLE:

The principle of balanced current protection of parallel feeders is based on the fact that when the impedances of the parallel lines are equal, the current in them are distributed equally under normal load conditions or under through-fault conditions. Any difference in impedances of the two feeders can be allowed for in the selection of the current transformer ratio so that the secondary currents of all transformers will be same when all paths are unfaulted. In the presence of short circuit on one of the feeders, the fault impedance of path 1 is reduced while that of path 2 is increased. Therefore greater portion of the fault current from sources passes through the faulty line while smaller part passes through the undamaged line. Thus similarity of the currents in the two feeders is disturbed at the source end, and it is therefore only necessary to compare the absolute magnitudes of the two derived currents from the two feeders to obtain definite criterian as to whether the fault is internal or external . The comparison is made electrically by means of a static balanced current relay in which case the alternating currents are rectified and compared in an amplitude bridge comparator circuit. The detailed description of operation of amplitude bridge comparator has already been mentioned. The relay unit with amplitude bridge comparator design is inherently a high speed device and readily bends itself to balanced current protection.

It may also be used for a similar protection at the receiving end of parallel lines provided there is an additional source of power supply at the receiving end which will increase the current in the faulty line at least 10 to 25%.

5.1.1. DESCRIPTION OF THE SCHEME USED:

The circuit used is shown in Fig. 20 . The operating current transformer ($T_{r.op}$) with one primary and secondary winding passes the current of the line to be protected. The restraining current transformer ($T_{r.R}$) has two primary windings W_{1r} and W_{2r} and one secondary winding $W_{3}r$. The current of the parallel line passes through primary winding W_{1r} of the restraining transformer ($T_{r.R}$). The second primary winding W_{2r} is connected in series with primary winding W_{1op} of the operating transformer ($T_{r.op}$).

The ratio of the primary winding W_{2r} is so adjusted with its secondary winding that it feeds only a fraction of the current of the protected line to its secondary circuit. The holding transformer ($T_{r.H}$) is supplied from a voltage transformer on the bus-bars of the protected section. The secondary windings of the operating, restraining and holding transformers are each connected to their respective restifier bridges B_1, B_2 and B_3. The bridges $B_2$and B_3 are connected in series winding and their combined output oppose the output of the rectifier bridge B_1 . The actuating relay is a polarised moving coil relay 'D_r' .

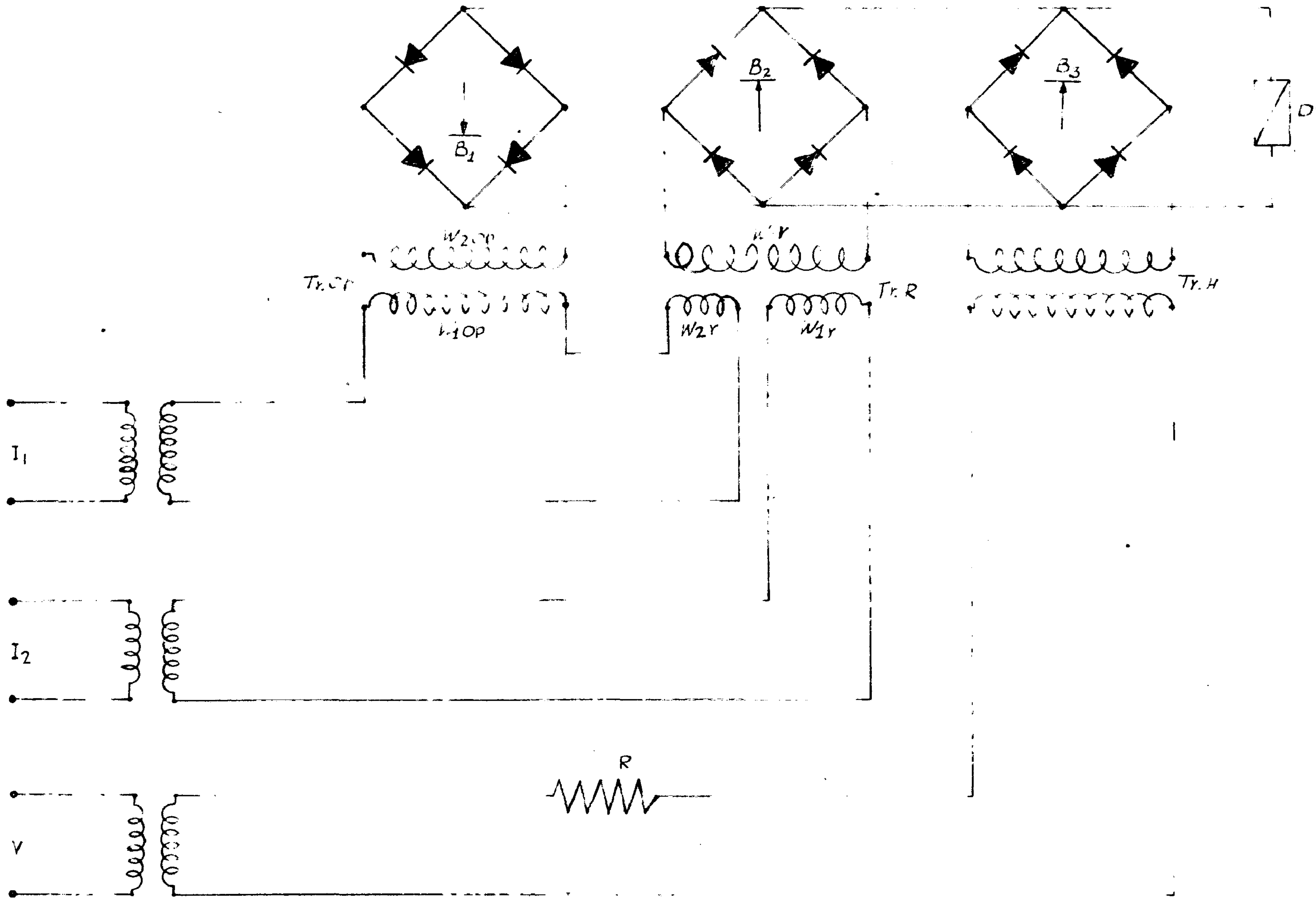


FIG. 20 FUNDAMENTAL CIRCUIT DIAGRAM OF THE RELAY.

The current from the primary winding W_{2r} is added to or substracted from the current in the primary winding 'W_{1r}' depending upon whether the currents in the protected feeder and the parallel feeder are inphase with each other or 180° out of phase. When the two currents are inphase with each other, then to balance a fixed value of the restraining current in the winding W_{1r}, the current in operating winding W_{1op} has to be large as compared to when the two currents are 180° out of phase. This results into automatic reduction in the slope of operating characteristics of the static relay when the two currents are 180° out of phase . This is a desirous feature at the receiving end station when it is relatively low powered and increases the fault current in the defective line by at least 10 to 25 percent.

The summation of operating, restraining and holding current takes place in differential circuit formed by the rectifiers. The actuating relay is supplied with the current in restraint or operate direction depending upon whether restraining current predominates the operating current or vice versa.

The turns ratio of the auxiliary current transformers are such that the relay restrains if the currents in the protected and parallel feeder are equal in magnitude. With a fault internal to the protected zone, the holding voltage collapses and current circuits are left in control to trip the faulty line.

5.1.2. STABILISATION AGAINST EXTERNAL FAULTS:

On the occurrence of external faults when the through current may greatly exceed the normal current, the current transformers may saturate . If the saturation conditions are not the same for transformers in both the feeders, the unbalance may be large enough to operate the relay. It is therefore necessary to stabilise the protection against external faults. Bias provides the necessary stabilisation.

The relay is given bias by adjusting the auxiliary current transformer ratios so that it will operate to trip one feeder when its current is some percentage above that in the other feeder. The percentage unbalance is choosen high enough to prevent false operation. The usual accepted value is 25% unbalance at sending end.

At the receiving-end of the parallel feeders where there is small additional source of power supply which will cause very small difference in magnitudes of the fault currents in the two feeders, the percentage unbalance choosen is small and the usual accepted value is 10% unbalance. Such a characteristic makes for wider applications of the balanced current relay.

5.1.3. DESIGN OF STATIC RELAY:

The relay is designed as three input rectifier amplitude comparator. The equation for operation is,

$$|S_{r1} + S_{r2}| < |S_o|$$

The three inputs are

$$S_o = I_1$$

$$S_{r1} = mI_2 \pm nI_1$$

$$S_{r2} = K \frac{V}{R}$$

Thus for operation

$$\left| mI_2 \pm nI_1 \right| \pm \left| K \frac{V}{R} \right| < \left| I_1 \right|$$

+ve sign when I_1 and I_2 are inphase -ve sign when I_1 and I_2 are 180° out of phase.

When one line is tripped out at receiving end i.e. when $I_2 = 0$, then

$\left| nI_1 \right| + \left| K \frac{V}{R} \right|$ must be greater than I_1 for the relay to restrain i.e. the restraining current provided by the holding voltage (V) must exceed the operating current provided by one line under maximum load conditions. This is essential to avoid non-selective operation of the relay under the influence of load current because in consequence of switch out of circuit breaker C.B.2 on feeder 1 (Fig. 21) will be an operation of relay 2 under the action of the working load current and tripping out sound feeder 2.

5.1.4. OPTIMUM VALUES OF 'm' and 'n' TO PROVIDE NECESSARY BIAS TO THE RELAY:

The particular relay designed by the author has 25% bias at the source end and 10% bias at the receiving end. Toppings are provided to vary turns ratio of the auxiliary transformers in order to adjust the slope of the operating characteristics to any desired value. The values of "m" and "n" to get the required slope are calculated as follows :

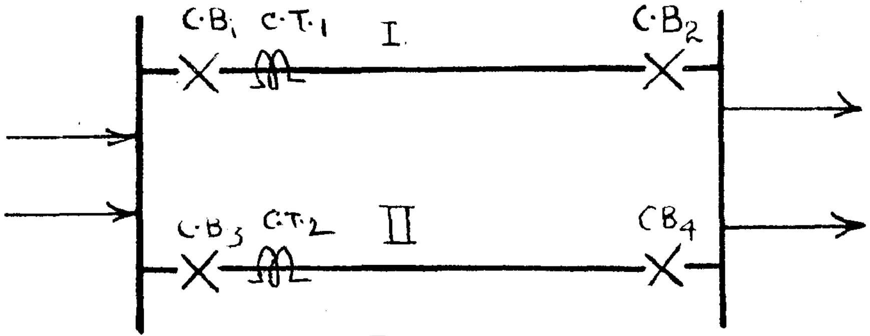


Fig 21

For the purpose of analysis we assume that with a heavy external short circuit, the current transformer $C.T_2$ to be saturated. This gives rise to a fault current I'_Δ in the secondary circuit, although the ratio of the two transformers has not been altered and the currents in the two feeders are equal in magnitude. Secondry current I_1 consists of one component I_D which may be inphase with current I_2 and the balance current $(I_1 - I_2 = I_\Delta)$ may have a phase different from that of I_2. Let ϕ be the phase angle between I_2 and I_D and the resulting phase angle between I_1 and I_2 be ψ.

For balance

$$|I_1| = |mI_2 + nI_1|$$

Refer to fig 22(c)

$$\text{or } |I_1| = \sqrt{|m^2I_2^2 + n^2I_1^2 + 2\,mnI_1I_2\cos\psi|} \qquad \text{-----(1)}$$

When $\psi = 0$

$$|I_1| = |mI_2 + nI_1| \qquad \text{-----(2)}$$

When $\psi = 180$

$$|I_1| = |mI_2 - nI_1| \qquad \text{-----(3)}$$

From equation (2) we have

$$\left| I_1 \right| = \left| mI_2 + nI_1 \right|$$

Dividing both sides by I_2 we have

$$\frac{I_1}{I_2} = m + n\frac{I_1}{I_2}$$

$$\frac{\text{Current in the faulty feeder}}{\text{Current in healthy feeder}} = m + n\,\frac{\text{current in faulty feeder}}{\text{current in healthy feeder}}$$

$$1.25 = n \times 1.25 + m \qquad \text{---(4)}$$

With $\psi = 180^\circ$ from equation (3) we have

$$I_1 = m\,I_2 - nI_1$$

or $$\frac{I_1}{I_2} = m - n\frac{I_1}{I_2}$$

$$1.10 = m - 1.1 \times n \qquad \text{---(5)}$$

Solving equations (4) and (5) for the values of m and n

$$1.10 = m - 1.1n$$

$$1.25 = m + 1.25\,n$$

we get

$$n = 0.0636$$

$$m = 1.17$$

Substituting these values of m and n in equations (2) & (3) we get

$$I_1 = 0.063\ I_1 + 1.17\ I_2$$

$$I_2 = 1.17\ I_2 - 0.0636\ I_1$$

or $I_1 = 1.25\ I_2$ at sending end

$I_1 = 1.10\ I_2$ at receiving end.

When $I_2 = 0$ i.e. when one of the feeder is tripped, then for balance point

$$|I_1| = \left\{ |nI_1| + \left|\frac{V}{R}\right| \right\}$$

$$\text{or } |I_1| = \left| \sqrt{n^2\ I_1^2 + \frac{V^2}{R} + 2\ nI_1 \frac{V}{R} \cos\ \theta} \right|$$

where θ is the phase difference between I_1 and V.

For $\theta = 0$

$$I_1 = nI_1 + \frac{V}{R}$$

$$I_1 = 0.064\ I_1 + \frac{V}{R}$$

$$0.94\ I_1 = \frac{V}{R}$$

$$\text{or } I_1 = 1.06\ \frac{V}{R} \qquad \text{---(6)}$$

Following two cases for holding voltage have tried to balance I_1 when $I_2 = 0$

Case 1: Feeder No. 2 is switched out at the receiving end station and the restraining current provided by the Full holding voltage is made to hold maximum load current of feeder No. 1.

Case 2 : Feeder No. 2 is switched out at the receiving end and the restraining current provided by the holding voltage for a through fault at the bushbars of the receiving end station is made to hold the minimum fault current of feeder No. 1.

Case No. 1.

Magnitude of full holding voltage = 110 V.

Assuming d.c. output current of bridge rectifier B_3 = 180 m.a.

(Rectifier B_3 is operated above its toe voltage).

To find the value of resistance R in voltage circuit

Referring to Fig. 22(d) and assuming 1 : 1 ratio of holding transformer $T_{r.H}$, then the value of R is

$$\frac{110}{R} = \frac{180}{1000}$$

$$\text{or} \quad R = 610 \quad \text{Ohms.}$$

To find the turns ratio of operating transformer ($T_{r.op}$)

When $I_2 = 0$

Let the maximum load current on feeder 1 = 6 amp.

Then from equation (6).

Then the ratio of operating transformer $= \frac{6 \times 0.94 \times 1000}{180}$

$$\frac{W_{2op}}{W_{1op}} \simeq 33$$

With values of $m = 1.17$ and $n = 0.064$, in order to have required percentage bias, the ratio of restraining transformer winding will be

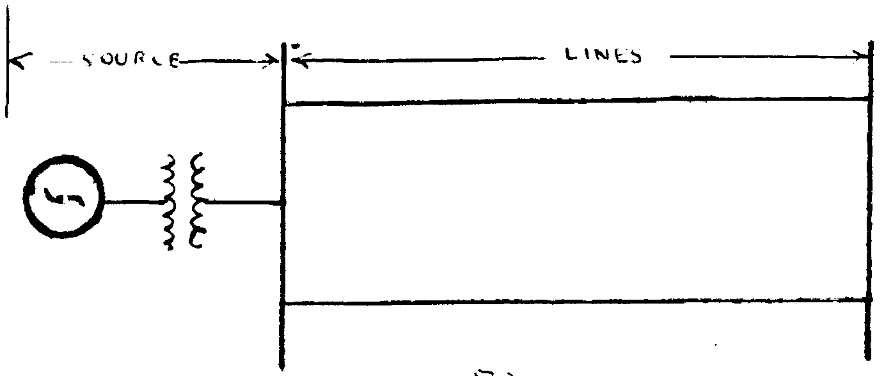


Fig 22(a)

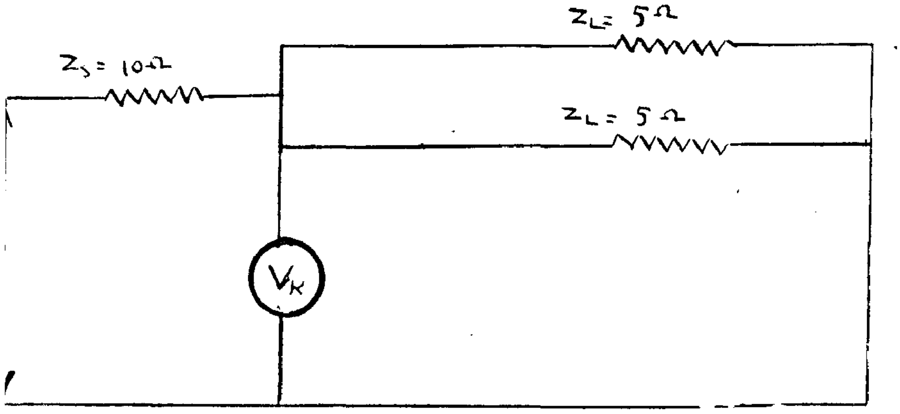


Fig. 22(a)

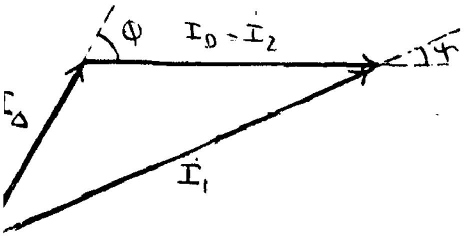


Fig 22(c) VECTOR DIAGRAM

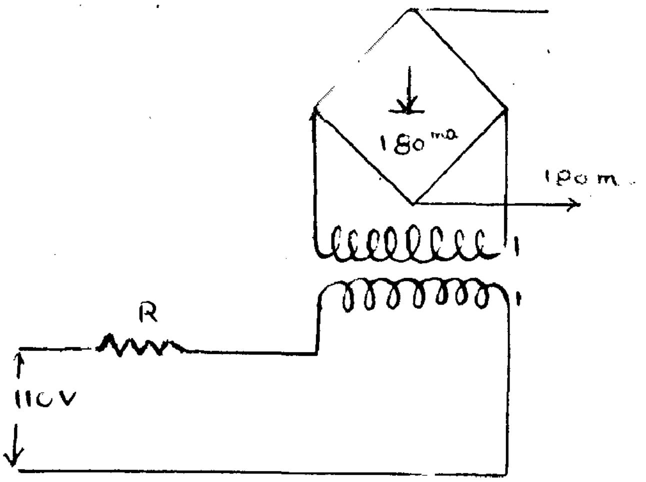


Fig 22(d)

$$\frac{W_{3r}}{W_{1r}} = \frac{33}{1.17} = 28$$

and

$$\frac{W_{3r}}{W_{2r}} = \frac{33}{0.064} = 515$$

The auxiliary current transformer have been designed at the working flux density = 7000 lines/sqcm with linearity upto 10 times the rated current of 5 amps. The number of turns calculated in each winding of each transformer are as follows :

W_{1op} = 34 turns
W_{2op} = 1122 turns
W_{1r} = 40 turns.
W_{2r} = 2 turns
W_{3r} = 1122 turns.

The fault currents in the two feeders and the fault voltages at sending end bus bars for faults at various position on feeder 1 of an assumed system (refer to Fig.22 a&b) are calculated and tabulated as below :

Table 1.

Fault position expressed as % of feeder length %	Fault voltage ~~voltage~~ V_R in V	Current in faulty feeder I_1 amps.	Current in Healthy Feeder I_2 amps.
80	21.3	5.31	3.6
70	20	5.85	3.1
60	19	6.37	2.73
50	17.5	7	2.25
30	12.5	8.3	1.5
20	9.0	9.1	1.0

The operating characteristics $I_{op} = f\ (I_r)$ of the relay unit designed are shown in Figs. 23, 24. Each graph refers to different percentage bias which is obtained by adjusting the turns-ratio of the restraining transformers.

The VA consumption in each circuit of the relay is given in Table no. 2.

Table No. 2.

VA -CONSUMPTION

Phase	Operating current circuit	Restraining current circuit	Holding voltage circuit
R	3·6 VA	4·75 VA	—
	2·75 "	6·25 "	4·4 VA

Case No.2

When feeder no. 2 is switched out at the receiving end i.e. $I_2 = 0$, the value of sending end voltage for a fault at receiving end busbar of the assumed system (refer to Fig. 22a, b) is equal to 37 volts.

The design of the scheme in this case is exactly similar to that of Case 1 except the magnitude of holding voltage = 37 volts and the value of R = 210 ohms. The turns ratio of the auxiliary current transformers are for operating transformer = 45 and for restraining transformer $= \frac{45}{1.17} = 38$.

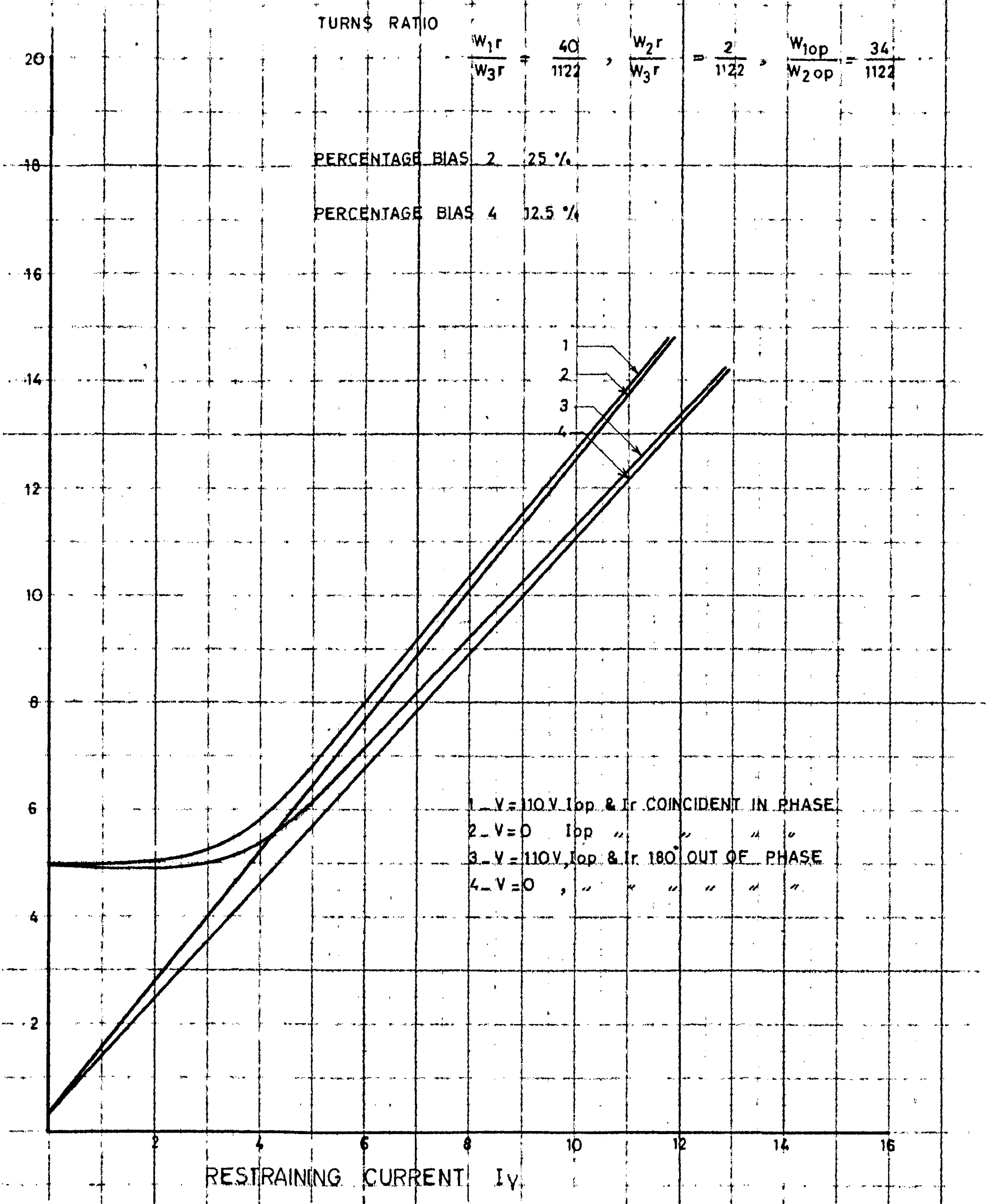


FIG. 23 CHARACTERISTICS $I_{op} = f(I_r)$

The number of turns calculated in each winding of each transformer are as follows :

W_{1op} = 25 turns.
W_{2op} = 1130 turns.
W_{1r} = 30 turns
W_{2r} = 2 turns
W_{3r} = 1130 turns.

The characteristics $I_{op} = f(I_r)$ for the relay - unit are shown in fig. 25 .

COMPARISON OF RESULTS OF CASE 1 and CASE 2.

The design in case 2 as compared to case 1 is made to hold feeder 1 when feeder 2 is switched out, under worst conditions (i.e. with fault assumed at the receiving end). However the comparison of the characteristics of each relay unit designed in both cases with values given in table No. 1 of currents in faulty and healthy feeder indicate that the length of dead zone in case 2 is large as compare to that in case 1.

The length of dead zone in case 1 is about 22% of total line length where as in case 2 it is about 40% of total line length. The permissible value is approximately 25%.

This discrepency in lengths of dead zones in two case is because of increased restraining effect provided by holding voltage in case 2 due to low value of resistance 'R' in the holding circuit. This makes the relay unit in case 2 less sensitive.

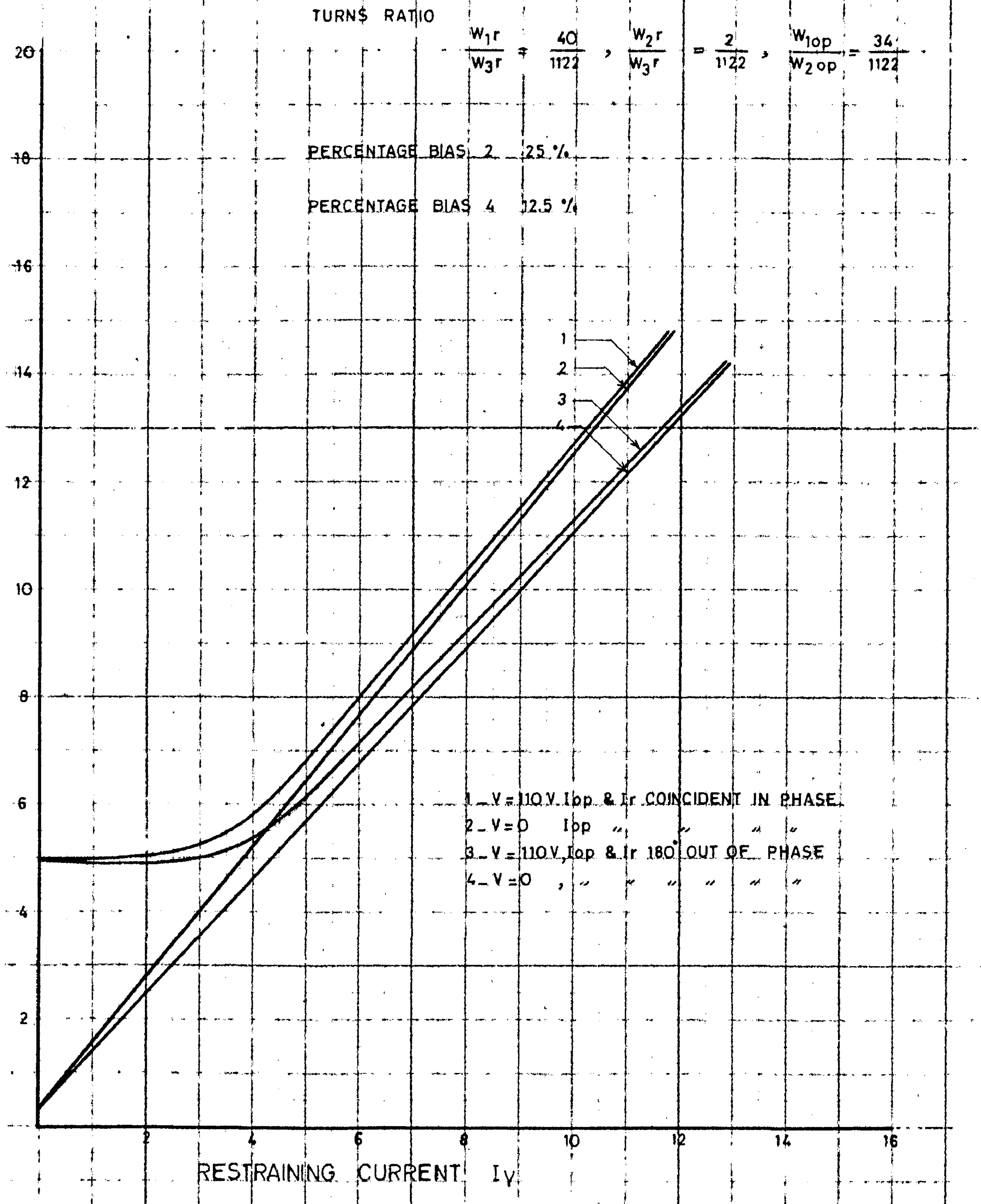


FIG. 23 CHARACTERISTICS $I_{op} = f(I_r)$

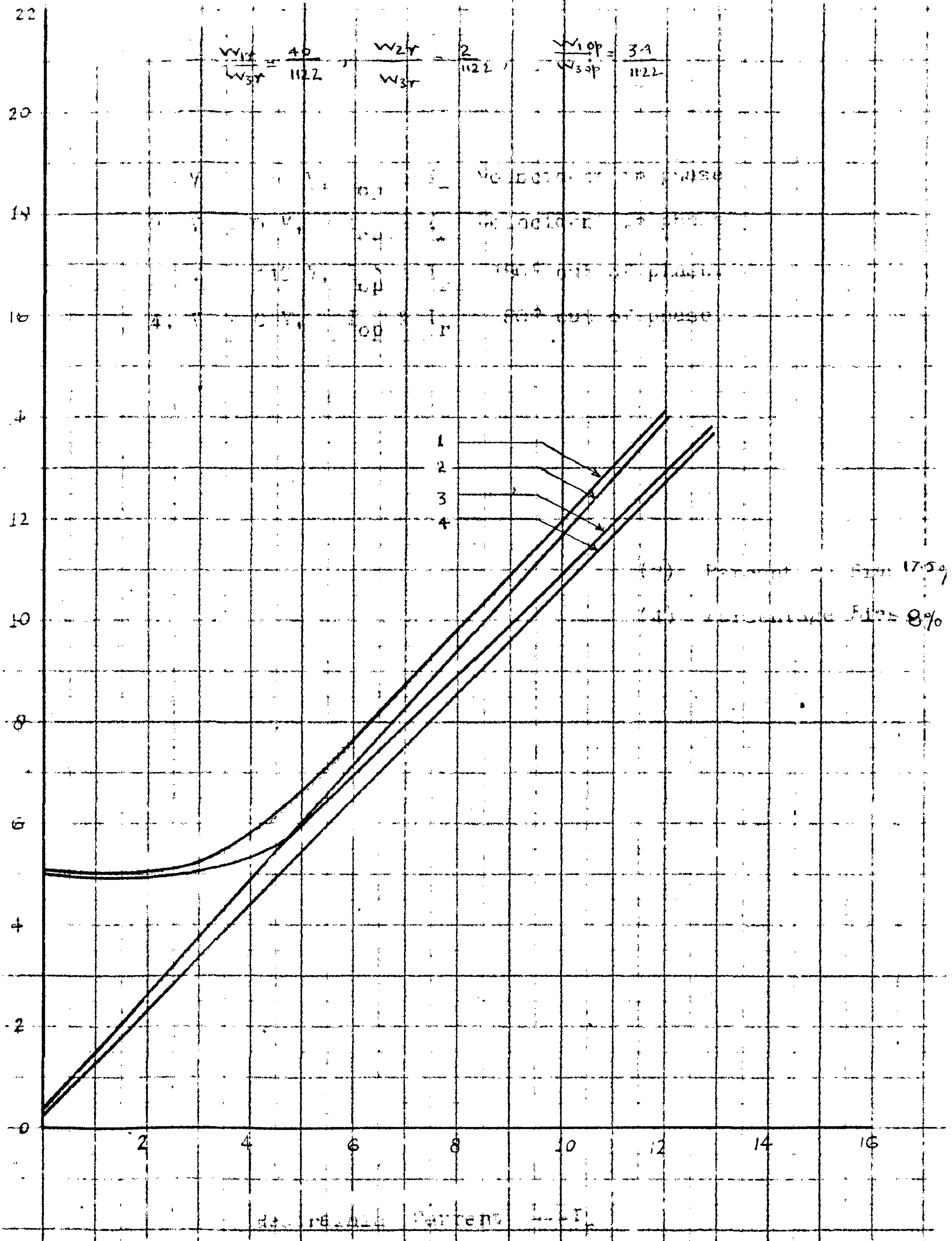


Fig. 24 [illegible] characteristic [illegible] r (I)

The number of turns calculated in each winding of each transformer are as follows :

W_{1op} = 25 turns.
W_{2op} = 1130 turns.
W_{1r} = 30 turns
W_{2r} = 2 turns
W_{3r} = 1130 turns.

The characteristics $I_{op} = f\ (I_r)$ for the relay - unit are shown in fig. 25 .

COMPARISON OF RESULTS OF CASE 1 and CASE 2.

The design in case 2 as compared to case 1 is made to hold feeder 1 when feeder 2 is switched out, under worst conditions (i.e. with fault assumed at the receiving end). However the comparison of the characteristics of each relay unit designed in both cases with values given in table No. 1 of currents in faulty and healthy feeder indicate that the length of dead zone in case 2 is large as compare to that in case 1.

The length of dead zone in case 1 is about 22% of total line length where as in case 2 it is about 40% of total line length. The permissible value is approximately 25%.

This discrepency in lengths of dead zones in two case is because of increased restraining effect provided by holding voltage in case 2 due to low value of resistance 'R' in the holding circuit. This makes the relay unit in case 2 less sensitive.

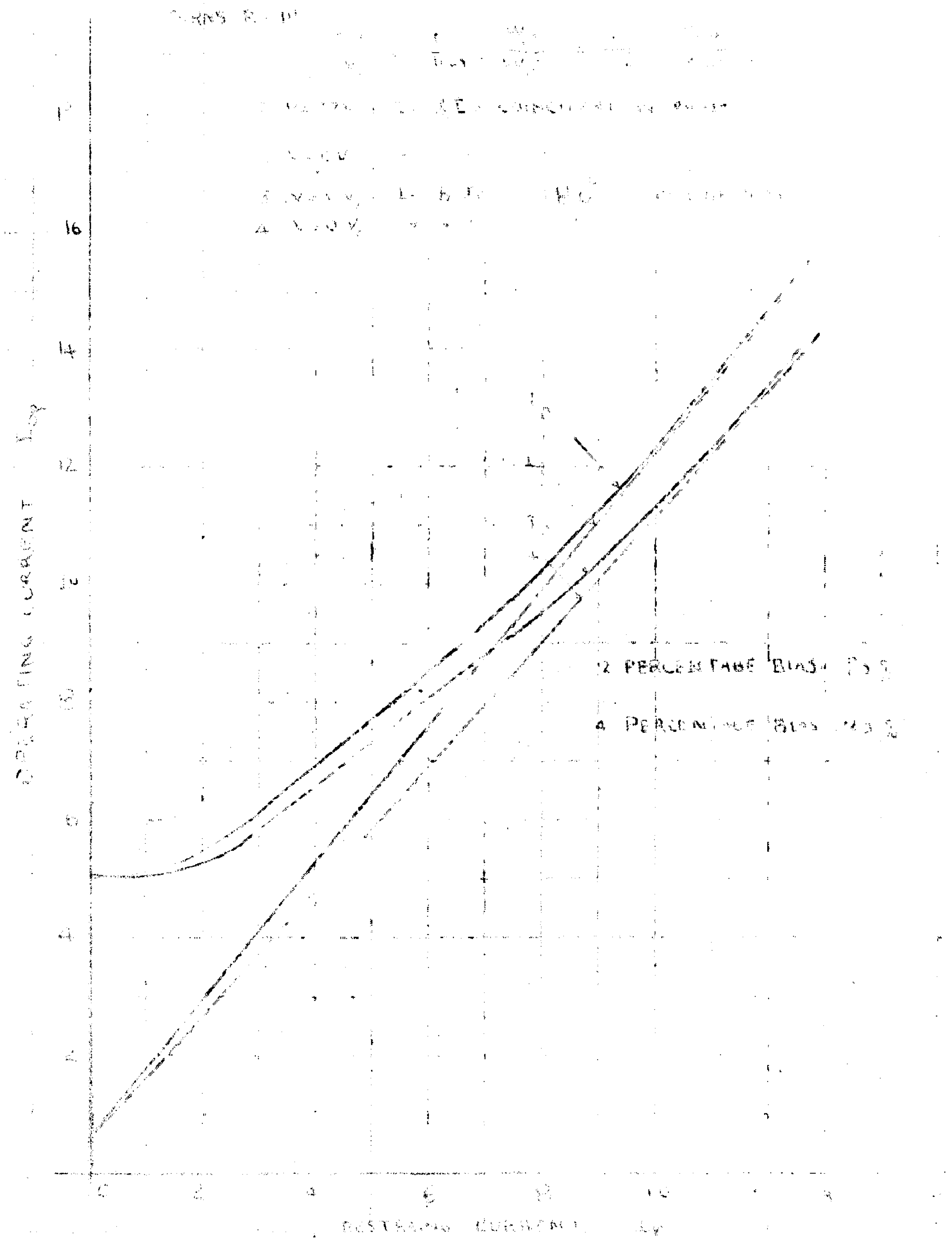


Fig 25 CHARACTERISTICS [illegible]

APPLICATION OF TRIGGER CIRCUIT:

It has already been mentioned that when operating and restraining inputs to the rectifier bridge amplitude comparator are not in phase, the voltage across the relay is a square wave. When $|m\, I_2 \pm |nI_1| + |\frac{V}{R}| = |I_1|$ the duration of the square wave output of the rectifier bridge comparator is equal and extends to 5 m.sec. on 50 cycle systems.

$$\text{When } |I_1| > |mI_2 \pm n\, I_1| + \left|\frac{V}{R}\right|$$

the positive half of the output voltage across the relay continues for more than 5 msec while the -ve half continues for less than 5 msec by the same interval. Under these conditions there is chattering of the moving coil relay and operation of the relay is not well defined. These defects can however be avoided with a trigger circuit. A transistor circuit could be arranged to trigger as soon as the positive half extends beyond 5 m.sec.

The circuit used as shown in Fig. 26 consists of

1. Emmitter-coupled trigger circuit as a level detector.
2. Asymetrical bistable circuit as slave element.

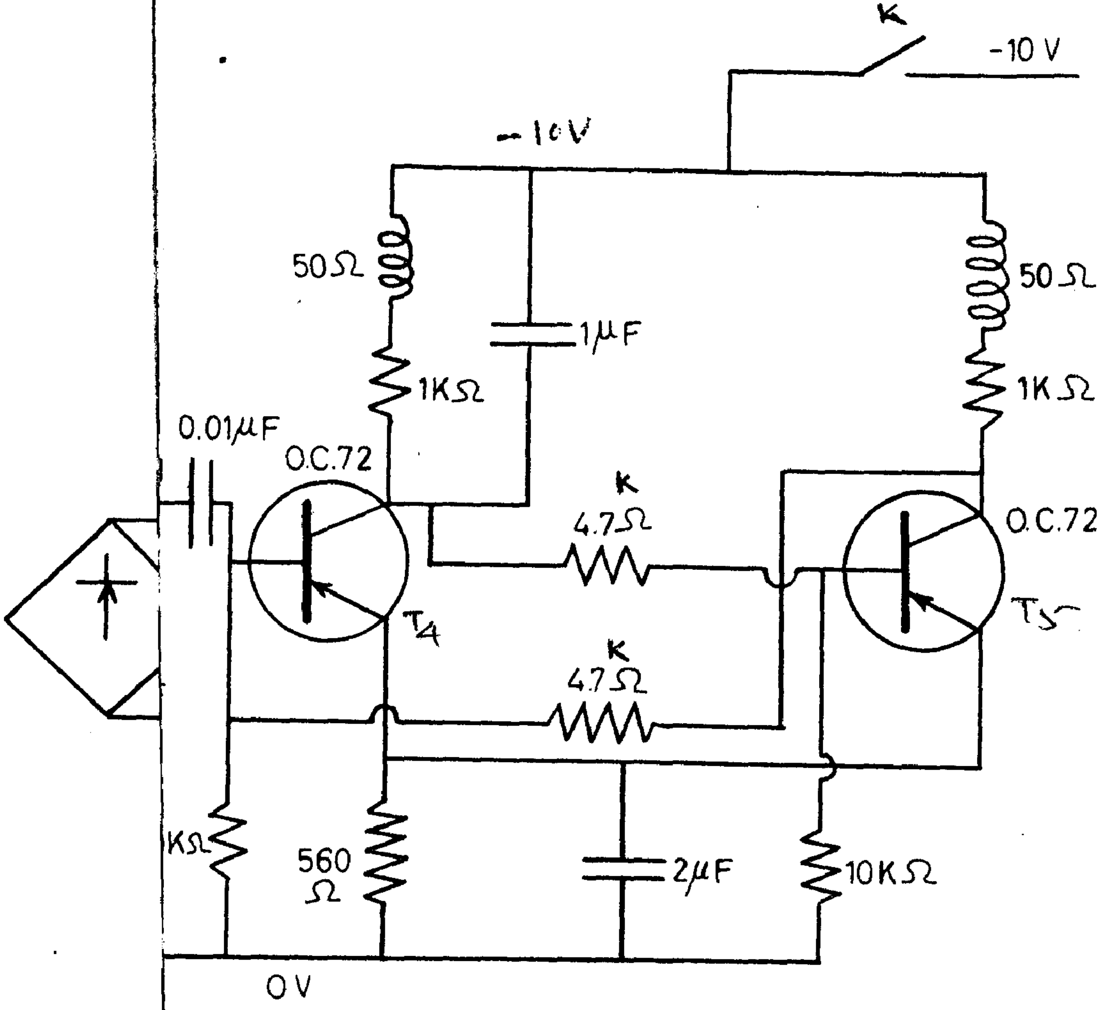
LEVEL DETECTOR:

It consists of three transistors T_1, T_2 and T_3. The emitters of T_2 and T_3 are connected through a common resistor R_{e23}. The circuit remains in one stable condition as long as the voltage V_c is lower than certain value V_p (the pick up voltage). As soon as the input voltage reaches this value the circuit suddenly changes to another stable state and output appears as a sudden change in voltage level.

When V_c is lower than the pick up voltage V_p, transistor T_3 is fully conducting due to - ve voltage applied to its base while transistor T_2 is biased to cut off by the voltage drop across the common emitter resistance R_{e23}.

When V_c reaches the pick up value, T_2 starts to conduct and its collector voltage starts to rise. This rise of voltage is transferred to the base of T_3 and reduces its emitter and collector currents.

This reduction in emitter current of T_3 pushes T_2 further to conduction with rise in its collector voltage which is again transferred to the base of T_3 and cycle is repeated. If during this action gain is greater than unity, the circuit will suddenly change to other state of stability where T_2 is fully conducting and T_3 is outoff.


K
-10 V
-10V
50Ω
50Ω
1μF
1KΩ
1KΩ
0.01μF
O.C.72
O.C.72
K
4.7Ω
T4
T5
K
4.7Ω
KΩ
560 Ω
2μF
10KΩ
0 V

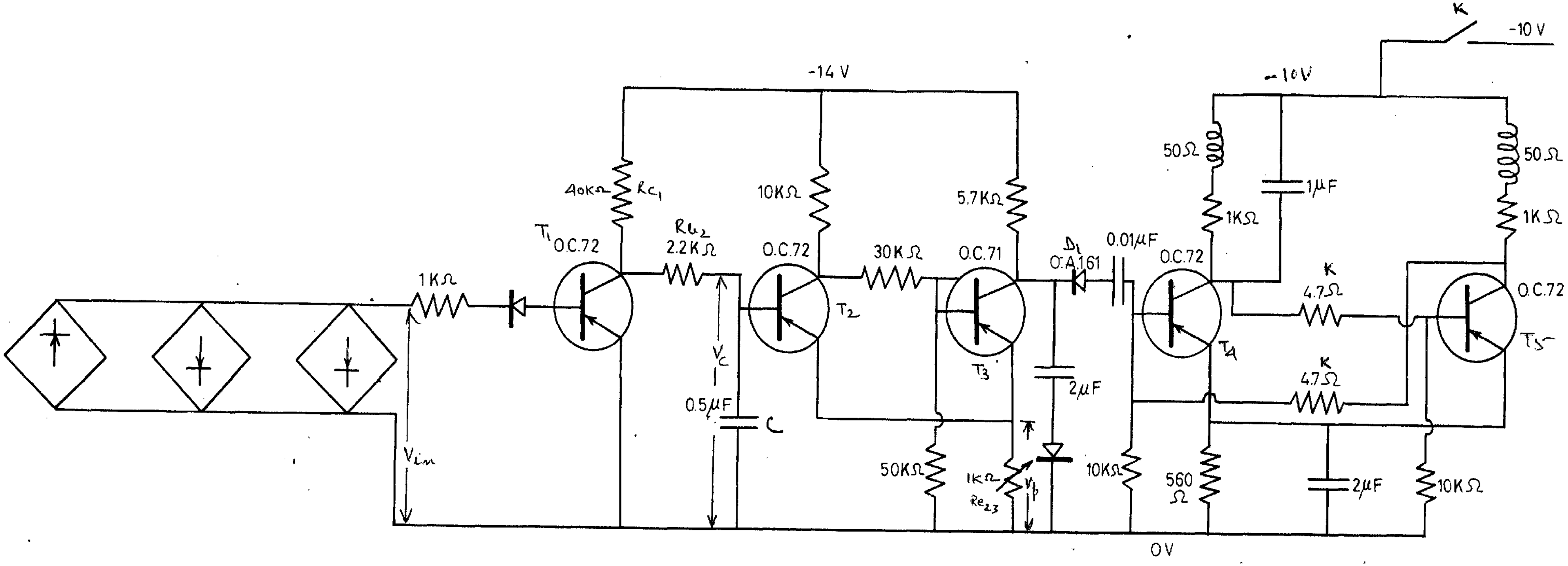


FIG. 26 LEVEL DETECTOR AND BISTABLE CIRCUIT

The input voltage (V_{in}), to the level detector is obtained from the rectifier bridge comparator such that the operating current I_1 makes the base of T_1 positive with respect to its emitter. When the base of T_1 is negative with respect to the emitter, it begins to conduct and $V_c \simeq 0$. When base of T_1 is zero or positive, transistor T_1 stops conduction and the voltage $-V_{cc}$ starts to charge the condenser 'C' and V_c starts to rise exponentially depend upon the time constant $C(R_{b2} + R_{c1})$ of charging circuit. As soon as the voltage V_c exceed the pick-up voltage V_p , the bend detector is triggered. By choosing proper values for R_{c1}, R_{b2} and C , V_c can be made to reach V_p if the base of T_1 remains at positive or zero poteitial for 5 m.sec.

$$\left| I_1 \right| > \left| mI_2 \pm nI_1 \right| + \left| \frac{V}{R} \right|$$

and the level detector triggers.

ASYMMETRICAL BISTABLE CIRCUIT:

The circuit has two states of stability in either of which one transistor is fully conducting and the other is cutoff and can remain in one of these states indefinitely The time constant of T_4 is made purposely made larger than that of T_5 so that collector voltage of T_5 will rise at higher rate than that of T_4. This is essential because when Switch K is closed both the transistors T_4 and T_5 race in conduction. The rise of voltage of T_5 is transferred to the base of T_4 and opposes its tendency to conduct, this further reduces the rate of rise of voltage of T_4 and the process is cumulative with the result that T_5 will be driven rapidly to full conduction while T_4 remains cutoff.

When the -ve pulse from the level detector (V_o) is applied to the base of T_4 through diode (D_1) the circuit is triggered, the H.T. supply is switched off and then switched on again by means of switch K, the original state of stability is re-assumed with T_5 conducting and T_4 cut off.

The operating characteristics $I_{op} = f(I_r)$ of the complete relay unit with triggering circuit are shown in figures 27, 28, 29.

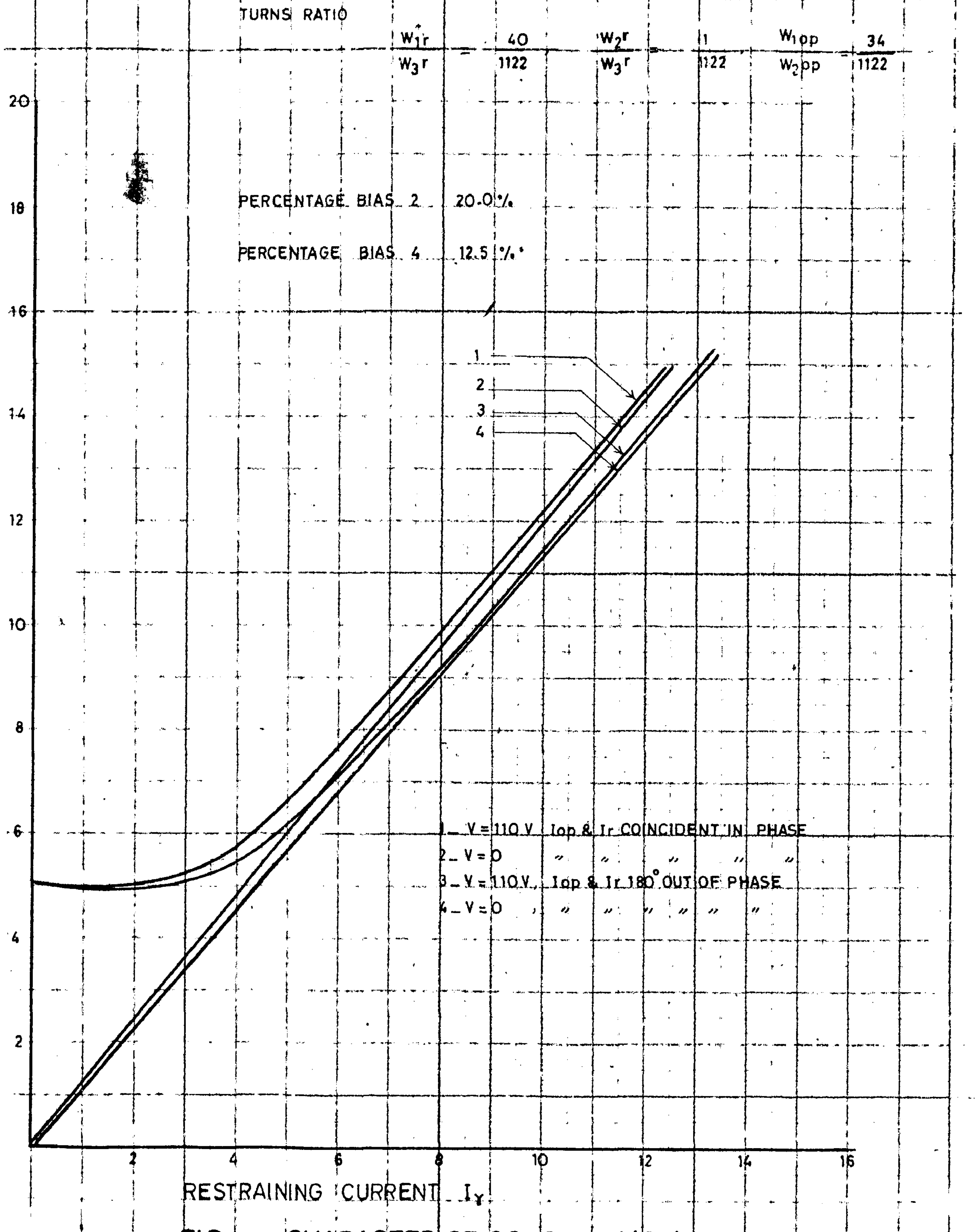


FIG. 27 CHARACTERISTICS $I_{op} = f(I_r)$

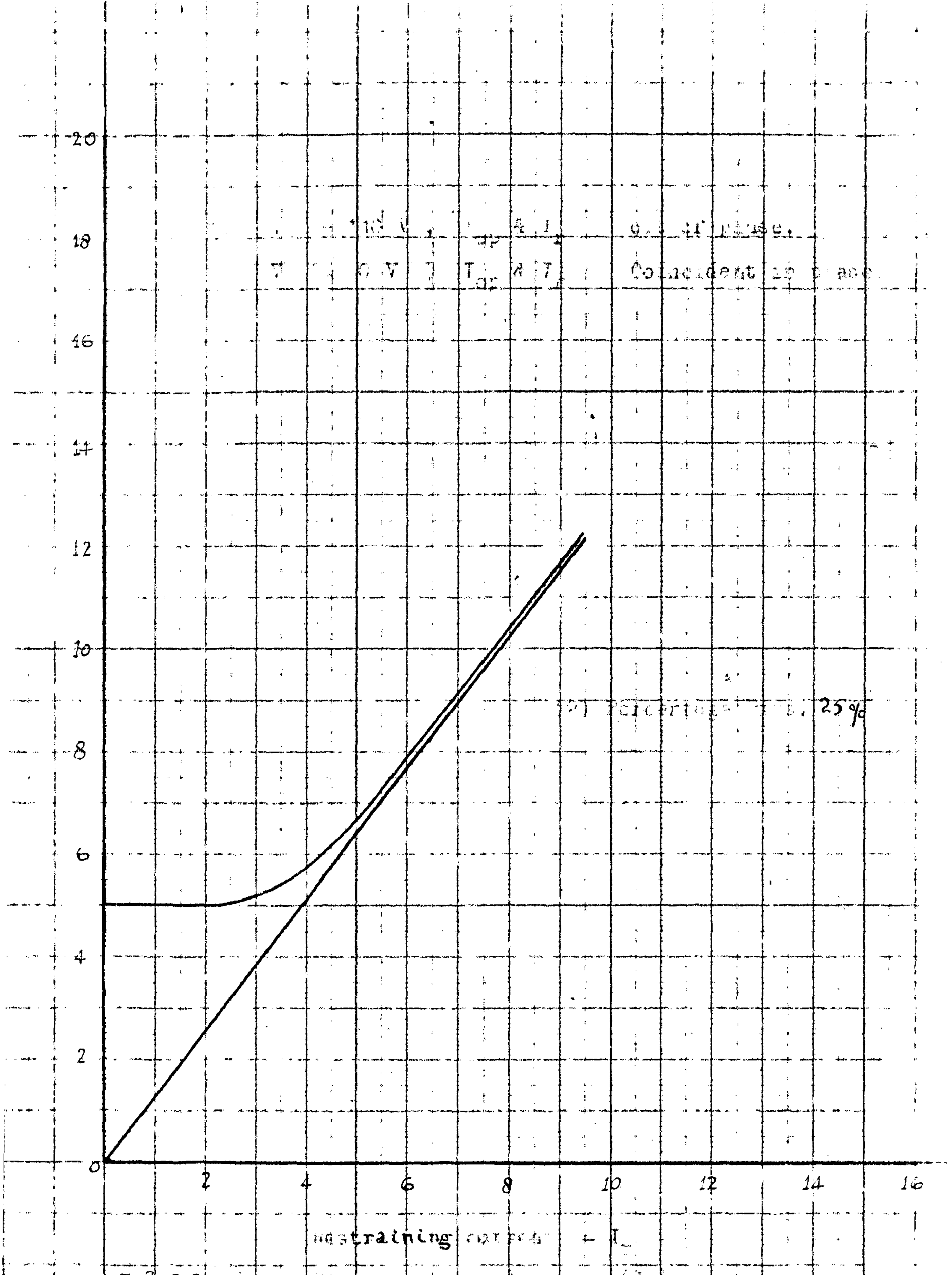


Fig. 29 Characteristic

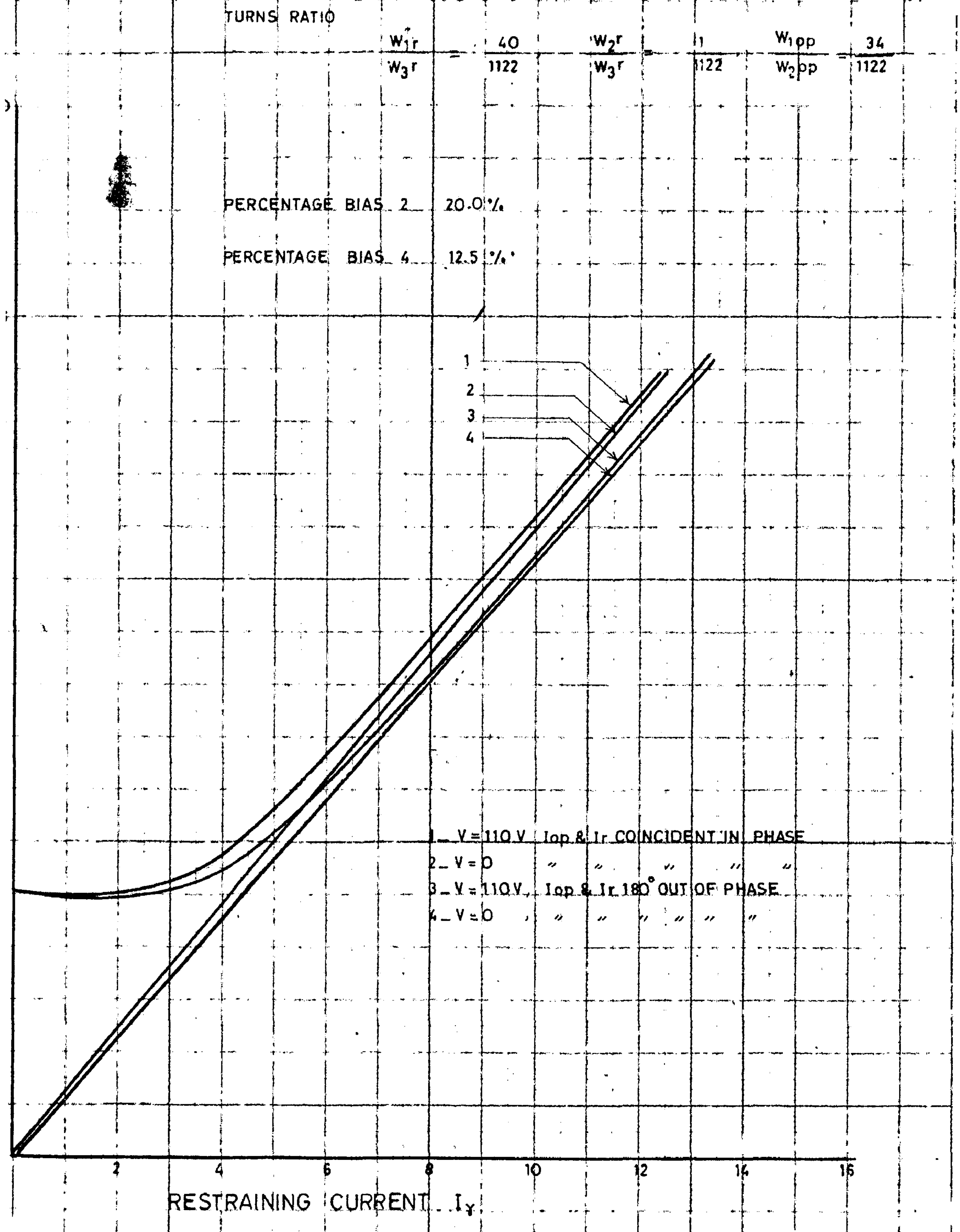


FIG. 27 CHARACTERISTICS $Iop = f(I_r)$

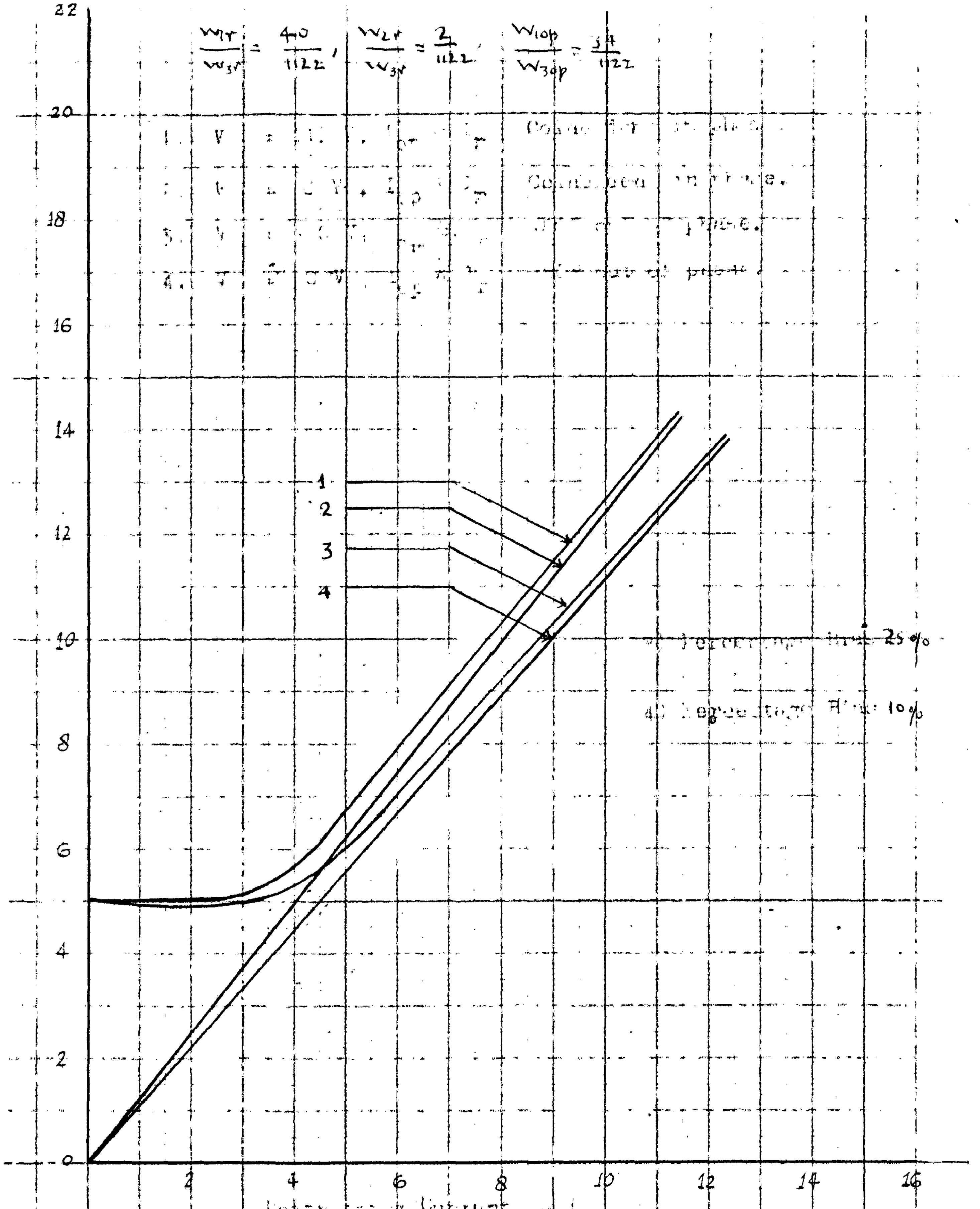
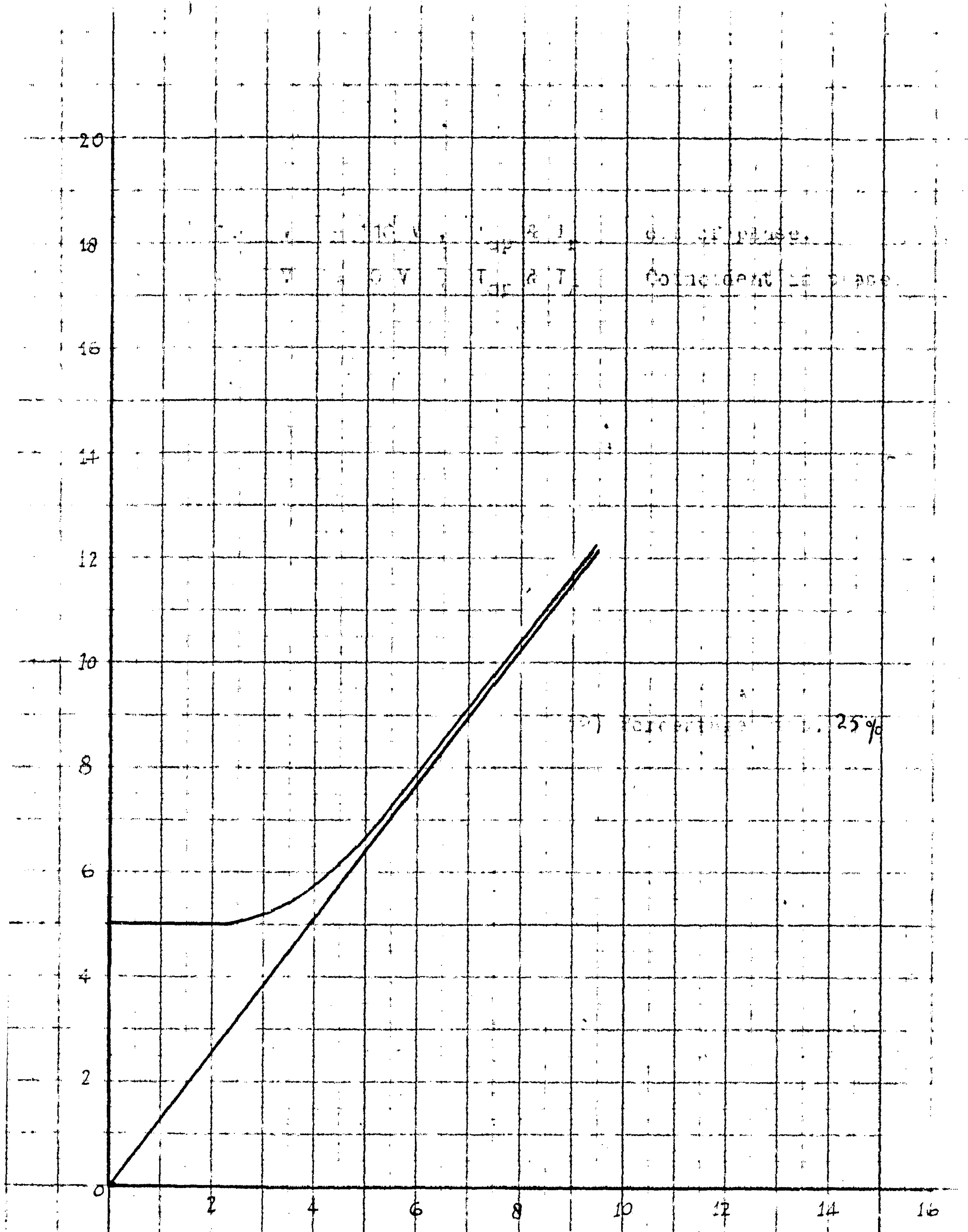


Fig. 28 Characteristics [illegible]



Restraining current – I_r

Fig. 29 Characteristic

CONCLUSION

With definite advantages claimed for, by d.c. relays over a.c. relays, electrical systems wherever possible, must be protected by d.c. relays. The characteristics $I_{op} = f(I_r)$ obtained by using three input rectifier bridge comparator are identical to those of electro-mechanical balance current relay. Therefore the parallel feeders may be protected by using this comparator unit. This static comparator unit has definite advantages over other static schemes for the protection of parallel feeders.

In the bridge circuit used, under normal conditions of operation of parallel feeders, when both the operating and restraining currents are equal in magnitude, the relay carries no current and the current flows through the rectifiers which work under short circuited conditions. The rise in power consumption is small. In other static schemes the power consumption is large as the rectified currents are compared magnetically in two seperate windings. Moreover the bridge comparator is acutely sensitive to small difference between operating and restraining currents. When the difference between the operating and restraining current is very large, the excess current after exceeding the threshold value, bypasses the relay. Accordingly at very high unbalance currents the rectifiers work practically short-circuited and are stressed only by the voltage due to their internal resistance. This bridge circuit , therefore protects the rectifiers against voltage stress and also the moving coil relay against over-loading. In other static schemes, both the rectifier unit and the relay must have more liberal design for there is no protection of relay against overloading and for rectifiers against over voltage . In the bridge circuit, the rectifiers are used as current convertors and therefore the change in forward resistance of the rectifiers with ageing does not effect the measurement of relaying quantities. The draw back of both, the Russian and author's scheme is that their use is limited only to the protection of two parallel feeders. The other static scheme can be used for the protection of multi-feeders. Russian static scheme also suffers from the disadvantage of time delay because of smoothening circuits.

Technologically the static relays are simpler to produce and dimensions are halved.

Although the electromechanical relay is still is predominant use and has proved its relaibility, the static relay and components are gaining acceptance. More time and experience are required before any absolute conclusions can be drawn regarding the reliability and the best static scheme.

APPENDIX 1

The volt-ampere characteristics of the three rectifier bridges used in the comparator are shown in Fig. 30 The characteristics for the three bridges are not identical . They are however made identical by putting a resistance of about 2 Ohms in the d.c. output side of the rectifier bridge 2. The identical set of characteristics so obtained is shown in Fig. 31 The "toe" voltage for each parallel path of the bridge is equal to 9 volts.

-0-

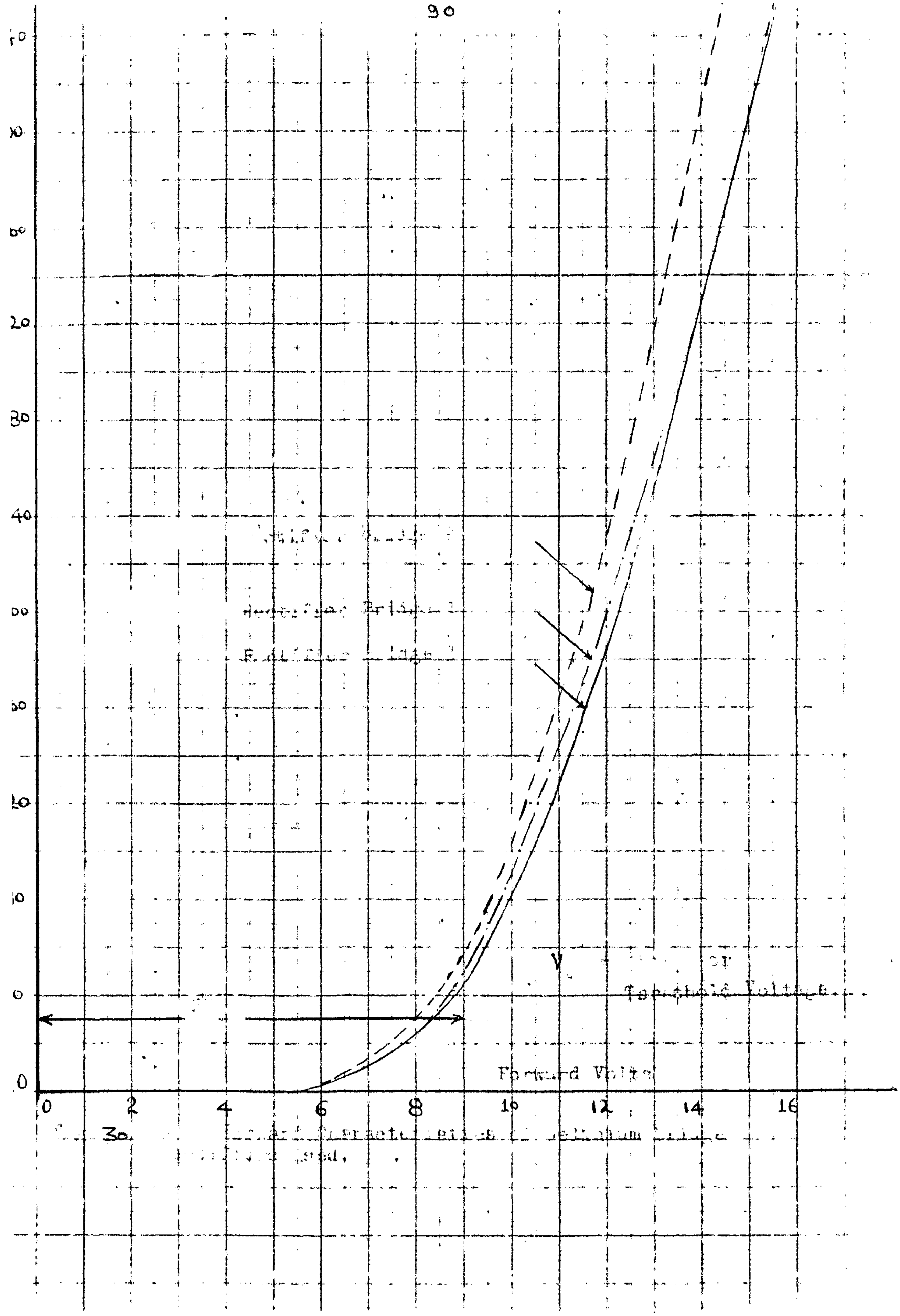
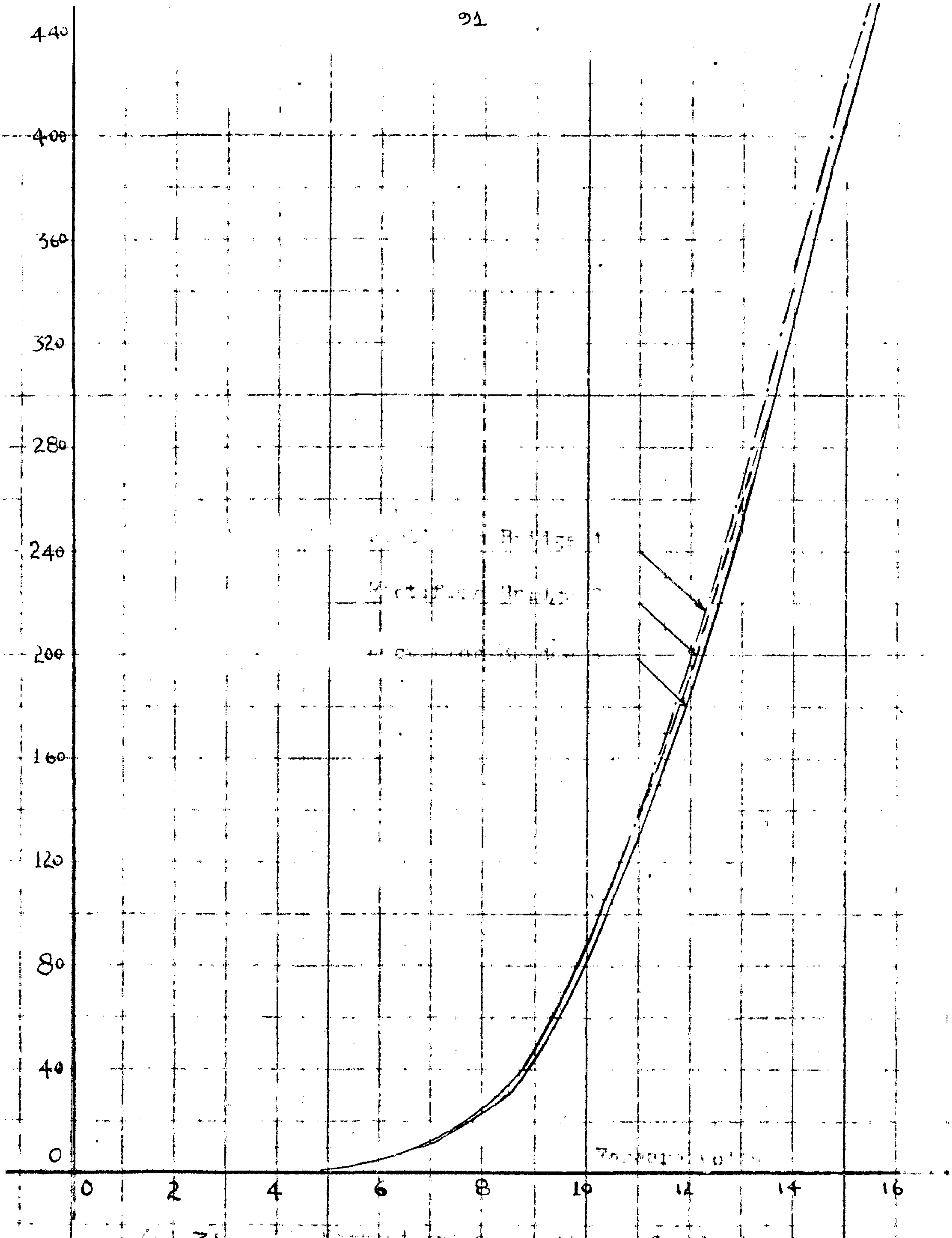


Fig. 3a. Forward Characteristics of Selenium Bridge [illegible] Load.


440
400
360
320
280
240
200
160
120
80
40
0
0
2
4
6
8
10
12
14
16
Bridge
[illegible]

31 [illegible]

REFERENCES

1. Braten, J.L. and Hoel, H. " A new High speed Distance Relay", CIGRE Paris 1950, Paper no.307

2. Smith, G.L." The application of High speed Parallel-feeder Protection-Gear," BTH Activities 19 Jan-Dec.1948.

3. Traver, O.C. and Kennedy, F.L."Modern Requirements for Protective Relays on Important System Interconnection". Transactions AIEE 49,1930, pp. 1226.

4. Circhton, L.N. "High Speed Protective relays," Transaction AIEE, 49, 1930,

5. Casson, W. and Last, F.H." Ultra High-speed Relays in the Fields of Protection and Measurement", Proceedings I.EE 96, Part II, 1949, pp. 50-56

6. Wideroe,R." Thyratron Tubes in Relay Practice" Transactions AIEE 1933, 53, pp. 1347.

7. Macpherson, R. . Warrington, A.R.Van,C and McConnel, A.J. "Electronic Relay Developments" Transactions AIEE, 1948, 67, part III pp. 1702.

8. Admson, C." Electronic Protection of Power Systems" Electrical Times, London,part1,June20,1957;part_II July 25th,1957, Part III,Oct3rd , 1957, Part IV Nov. 7th, 1957; Part V, Feb. 27th 1958; Part VI March 6th, 1958.

9. Loving, J.J."Electronic Relay Developments" Trans.AIEE, 1949, 68, Part I, pp. 233.

10. Bergseth, F.R. " An electronic Distance Relay Using a Phase Comparison Principle", Trans. AIEE 1954,73 pp. 1276.

11. Adamson, C. and Wedepohl, L.M. "Power System Protection with particular reference to the Application of Junction Transistors to Distance Relays," Proc. IEE 1956, 103, part A, pp. 379.

IEE

12. Kennedy, L.F., "Electronic Relaying Provides Faster Fault Clearing Times", CIGRE; Paris, 1954, paper No.332.

13. Adamson,C. and Talkhan, E.A. "The Application of Transistors to Phase Comparison Carrier Protection" Proc. IEE, 1959, 106, Part A

14. Adamson, C. and Wedepohl, L.M. "A Dual-Comparator Mho-type Distance Relay utilising Transistors," Proc. IEE 1956, 103, part A, pp. 509.

15. Ungenetze, S.D. "Schnell Distanz-Relais fur Mittelspan AEG Prospectus, K-9 Ffm 5715.

16. Neugebauer,H."D.C. or A.C.Relays of Selective Protective Systems" CIGRE Paris,1958,paper No.348 Part 3,4.

17. Possner, O. "The Protection of Double and Multi-circuit Lines" CIGRE Paris, 1962, Part 3,4 Paper No.327.

18. Lewis, W.A. and Tippett, L.S., "Fundamental Basis for Distance Relayeing on 3-ϕ Systems" Trans. AIEE 1947, 66, pp. 694-709.

19. Rao, T.S.M. " Rectifier Behaviour in Static Amplitude Comparison", Jr. of the Institute of Engineers (India) Electrical Engineering Division June 1965, Vol. 45, No10 Part E-L-5.

20. Grinshtein and Rakmanou. I.A. "Semi-conductor Balanced Current Relay". Electric Technology, USSR, Vol. 4, 1963.

21. Ryder, C; Rushton, J ; and Pearce. F.M. "A Moving-coil Relay applied to Modern High Speed Protective systems" proc. IEE 1953, 100, part II pp. 261.

22. Mathews, P. and Nellist, B.D. "Generalised circle diagram and Protective gear," Trans. IEEE (Power apparatus and systems) 1964, 83, pp. 165.

23. Supplement to Recent Practices and Trends in Protective Relaying IEEE Committee Report Transaction IEEE (Power apparatus and systems) 1964, 83, pp. 165.

24. Galvin, T.J., Greiner, R.A. and Swift, W.B; "Switching Levels in Transistor Schmitt Circuit", IRE Transactions on Instrumentation, Dec. 1960, Vol. 1-9, pp. 309.

OTHER REFERENCES

BOOKS.

25. Warrington, A.R. Van C., "Protective Relays, Their Theory and Practice", Chapman and Hall, 1962.

26. Atabekov, G.I., " The Relay Practice of High Voltage Networks" Pergaman Press.

27. Titarenko, M. and Noskov - Dukelsky, I. "Protective Relaying in Electrical Power Systems" Foreign Language Publishing House, Moscow.

28. Kaufmann, M. "The Protective-Gear HandBook", Pitman and Co. Ltd.