NVESTIGATION OF THE EFFECT OF SERIES CAPACITORS ON THE PROTECTION OF POWER SYSTEMS

A Dissertation
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MASTER OF ENGINEERING
in
POWER SYSTEM ENGINEERING

by
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CERTIFICATE

Certify that the dissertation entitled "INVESTIGATION OF THE EFFECT OF SERIES CAPACITORS ON THE PROTECTION OF POWER SYSTEMS", which is being submitted by Sujit Kumar Barua in partial fulfilment for the award of Degree of Master of Engineering in "Power System Engineering" of University of Roorkee, is a record of candidate'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 nine months from January to September, 1968 in preparing this dissertation for Master of Engineering Degree at this University.

Dated 23rd Sept. 1968

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ABSTRACT

In this dissertation the various aspects relating to the use of series capacitors in the power systems have been discussed.

To obtain the best location and optimum compensation of the series capacitor, for a particular system, the cost calculation has been carried out.

The method of protection of the series capacitor have also been discussed.

Lastly the effect of series capacitor on various protective relays has been analysed and some suitable protective schemes have been suggested.

LIST OF SYMBOLS

Z_L = Line Impedance
$Z_s\underline{/\theta_S}$ = Source Impedance
R_L = Line Resistance
X_L = Line Reactance
X_C = Reactance of Series Capacitor
Z_o = Surge Impedance of Compensated Line
Z_o' = Zero Sequence Impedance of the Line.
E_s = Sending end Voltage
E_r = Receiving end Voltage
P_r = Receiving end Power
δ = Power angle.
V = Line Voltage
I = Line Current
θ = Load power factor angle.
V_L = Fault Voltage at relay terminal.
I_L = Fault Current at relay terminal.
ϕ_L = Angle of Fault Current.
T = Torque Developed in Directional relay.
K' = Relay Constants.
V_{bc} = Polarising Voltage of Directional relay.
α = Internal relay angle.
ϕ_r = Angle of Fault Current in Directional relay w.r.t. Polarising voltage.
n = Number of equal length of Line section.
K = Degree of compensation, (series capacitor reactance)/(Total line reactance).
K'' = Degree of compensation by the capacitor located at intermediate busbar for method 4.

X_1 = Unswitched series capacitor in busbar of intermediate sub-station.

X_2 = Switched series capacitor in busbar of intermediate sub-station.

MT = Mho, tripping relay.

MB = Mho, blocking relay.

OM = Mho relay, for starting phase comparison carrier relay.

S_1, S_2, S_3
and S_4 = Input Signals to static phase comparator.

$Z_{R1}\underline{/\theta_1}$ and
$Z_{R2}\underline{/\theta_2}$ = Replica Impedance of the line.

ϕ = Coincidence angle of static phase comparator.

β_1, β_2 = Limits of Coincidence angle for static phase comparator No.1.

β_3, β_4 = Limits of Coincidence angle for static phase comparator No.2.

τ_b, τ_c = Time delay given to Static phase comparator.

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CHAPTER 1

INTRODUCTION

1.1. IMPORTANCE OF SERIES CAPACITOR IN POWER SYSTEM:

The series capacitor is used to improve the operation of both transmission and distribution circuits. In a distribution system, it is used to improve the voltage regulation and lamp-flickering, whereas in a transmission system it helps to improve the line capability and to obtain the desired load distribution in parallel feeders.

1.2. USE OF SERIES CAPACITOR IN DISTRIBUTION LINE:

In case of radial feeders with series capacitor compensation, the voltage drop is given approximately by the following equation:

$$IR_L \text{ Cos } \theta + I\,(X_L - X_C)\text{Sin } \theta \qquad \ldots \qquad (1.1)$$

where, R_L, X_L are the resistance and reactance of the line, X_C is the reactance of the series capacitor, I is the load current and θ is the power factor angle of the load. If $X_L=X_C$ (i.e. 100% compensation), the voltage drop becomes IR_L Cos θ only. The equation (1.1) shows that the series capacitor can reduce the voltage drop only when the power factor is lagging and it becomes more effective in case of low power factor angle.

The series capacitor is quite capable of reducing the lamp flickering. It is inherently automatic in operation as it introduces a 90° leading voltage directly proportional to the current. This capacitive voltage compensates instantaneously the inductive voltage for all values of current - thus reduces the rapid voltage dips and the lamp-flickering.

1.3. USE OF SERIES CAPACITOR IN TRANSMISSION LINE:

In transmission line power transfer between the sending end and the receiving end, the line loss being neglected, is given by equation (1.2)-

$$P_r = \frac{E_s . E_r}{X_L} \sin \delta \quad \ldots \quad \ldots \quad (1.2)$$

where,

P_r = Power received at the receiving end.

E_s, E_r = Sending end and receiving end voltages.

X_L = Line reactance

δ = Power angle.

From the equation (1.2) it is clear that power transfer is inversely proportional to line reactance.

The reactance of the overhead transmission line can be decreased by any one of the following four methods.

(1) Higher voltage.

(2) Multiple parallel lines

(3) D.C. Lines

(4) Series Capacitor.

1.3.1. High Voltage Operation:

Extra high voltage transmission system has already been adopted to transmit large blocks of power over a long distance. The recent developments in high voltage technique, have made possible to design a line to operate at voltages as high as 750 KV.

But the large capital investment on extra high voltage line above 400KV may not be economically justified in all cases. Moreover, it is found that owing to stability limitations and reactive power requirements, most of the existing lines, can not be loaded more than 75%, of the magnitude required to develop minimum annual costs per Kwhrs transmitted.

So it calls for the consideration of the usefulness of other methods before adopting higher and higher voltages in a.c.

transmission.

1.3.2. Parallel Feeders:

With the increase of number of parallel feeders, the system transfer impedance decreases, consequently power transfer increases. Stability limit of the system can be further increased by sectionalizing the parallel feeders at several points. But as the cost increases with number of parallel feeders and number of sectionalizing substations, this method does help appreciably in improving the economic loading status of the long high-voltage line.

1.3.3. D.C. Transmission System:

In d.c. system, power flow between the two ends is determined by the difference of magnitudes of the voltages at the two ends. It has been found that for the given circuit, having the same conductor, same insulation level and for the same transmission efficiency, the power transfer capacity in d.c. line is twice than that of an a.c. line. Further there is no question of stability limit in a d.c. line. For the transmission of large amount of power over a distance longer than 500 miles, d.c. system is undoubtedly preferable to the present a.c. system.

Disadvantage lies with d.c. system is that it is not suitable for supplying power to the intervening areas as there is no d.c. equivalent of an a.c. transformer.

1.3.4. Series Capacitor:

The series compensation is the easiest means to decrease the line reactance. It can be obtained by using static capacitors in series with the transmission line. The power transfer with series capacitor in line is given by the following equation.

$$P_r = \frac{E_s \cdot E_r}{(X_L - X_C)} \sin\delta \quad \ldots \quad \ldots \quad (1.3)$$

where,

X_C = Reactance of the series capacitor.

Thus by the introduction of series capacitors, the active power transfer can be increased. The transient stability limit will also be increased. Over and above the surge impedance of the line is decreased, thereby increasing the surge impedance loading of the line. The surge impedance loading is given by E_r^2/Z_0, where E_r is the receiving end voltage and Z_0 surge impedance of the compensated line.

1.4. LOAD DISTRIBUTION OF PARALLEL FEEDERS:

The load distribution of the parallel lines depends upon the R_L/X_L (resistance/reactance) ratio of the line. Therefore for equal distribution of loads the series capacitors can be used with advantage.

1.5. THE SIZE, LOCATION AND PROTECTION OF THE SERIES CAPACITORS:

Discussed in details in next chapters.

1.6. PROBLEMS ASSOCIATED WITH SERIES CAPACITOR APPLICATION:

These problems are:

(1) Distorted and excessively large transformer exciting currents at the time of energisation of an unloaded transforme bank, commonly known as "Ferroresonance".

2. Hunting of lightly loaded synchronous motors.

3. Self excitation of induction motor and induction start synchronous motor.

"Ferroresonance" can be avoided by shunting the capacitors with resistors or by having a certain amount of load on the load side of the series capacitors.

Hunting of synchronous motor becomes prominent if R_L/X_L ratio of the system upto motor terminal is greater than unity. This possibility is quite remote in transmission line because of the fact that the value of resistance is low and compensation does not exceed more than 70% in transmission line.

Due to presence of series capacitors in the line, induction motor and induction start synchronous motor may fail to pull upto the normal operating speed at starting. This is known as "Self excitation". The effect of "self excitation" can be reduced by using shunt resistor across the capacitors.

The problems discussed above are more important for series compensated distribution line, whereas protection becomes the major problem for the series compensated transmission line. Most of the conventional protective schemes do not work properly in series compensated lines. Depending upon the location and the degree of compensation, the series capacitors will introduce various relaying problems, resulting in increased fault clearing time, loss of selectivity and incorrect relaying operation.

1.7. SERIES CAPACITOR PROJECTS AND EXPERIENCE:

Series Capacitor has already been adopted for the compensation of long high voltage transmission lines in many countries. Som of the schemes are as follows.

1.7.1. Swedish Scheme:

In Sweden, the series capacitor compensation scheme for 400KV trunk lines was first introduced in 1954. The estimation made lateron that by the introduction of series capacitors in the trunk line, the total power loss is reduced by 15 MWs and specific transmission cost by 15%. Total 950 MVAr of series capacitor was installed in six 400 KV substations. Under Swedish conditions the series capacitors were located out on lines near to the receiving end. No major trouble is experienced so far in these installations.

1.7.2. Russian Scheme:

The series capacitor installation of 486 MVAr was completed and put into operation in Kuisbiskev-Moscow transmission line in 1958. It consists of three parallel lines of equal carrying capacity. In case one line is out of commission, other two lines will be able to transfer the total power with the help of increased series capacitive reactance.

Paper oil capacitors each having power rating of 50 MVA, rated voltage of 600V and reactance of 7.2 ohms were used. 9720 capacitors were necessiated to obtain the rated current of 2,250A and reactance of 32 ohms equal to 25% of the total line reactance.

The following types of protection were adopted.

(1) Protection against the break-down of the plates and casing is given by cross wire connection made at every two series connected capacitors units in the phase and also by installing the capacitors in groups on platforms insulated from each other.

(2) Protection against the internal short circuits has been provided by sectionalizing current limiting buses.

(3) The protection against the excessive voltage across the capacitor, due to fault current, is provided by means of air blast shunting arrestor.

(4) Damping arrestor of the order of 7 ohms in parallel with 1.2 mH coil is used to damp out the oscillations which occur due to break down of the airgap of the series capacitor. All the capacitors are insulated from the ground at a

voltage of $400/\sqrt{3}$ KV. It is found that the transfer capacity of the transmission system is raised by 350 MWs.

1.7.3. Japanese Scheme:

It is a typical example showing how desired load sharing in the parallel lines can be achieved, with the help of series capacitors, by making R_L/X_L ratio of the lines equal.

In the Japanese 220 - 110 KV Fukuoka and Oyodo loop system the desired power flow control is obtained with the help of series capacitors and the phase shifting transformers.

TABLE No.1.1.

Line	Length (Km)	Impedance (R_L+jX_L) ohms	R_L/X_L	Remarks
220KV Central trunk line	134.6	4.64+j32.15	$\frac{1}{6.94}$	Transmission line only.
		4.64+j100.45	$\frac{1}{21.7}$	including sending end and receiving end transformers.
110KV West	157.6	12.87+j38.82	$\frac{1}{3.02}$	Transmission line only.
110KV East	186.5	13.7+j42.94	$\frac{1}{3.14}$	Transmission line only.

As shown in Fig.(1.1) and also from the Table No.1.1, R_L/X_L ratio of 220KV line is much lower than that of 110KV line. To make the ratio R_L/X_L equal, the use of series capacitor was found to be economical and 200% compensation of 220KV line was required for this purpose. But instead 144% compensation and phase shift of 7.8° with the help of phase shifting transformer was given on relaying consideration. The series capacitor is installed at the receiving end together with the shunt capacitors to obtain the effective phase modifying operation.

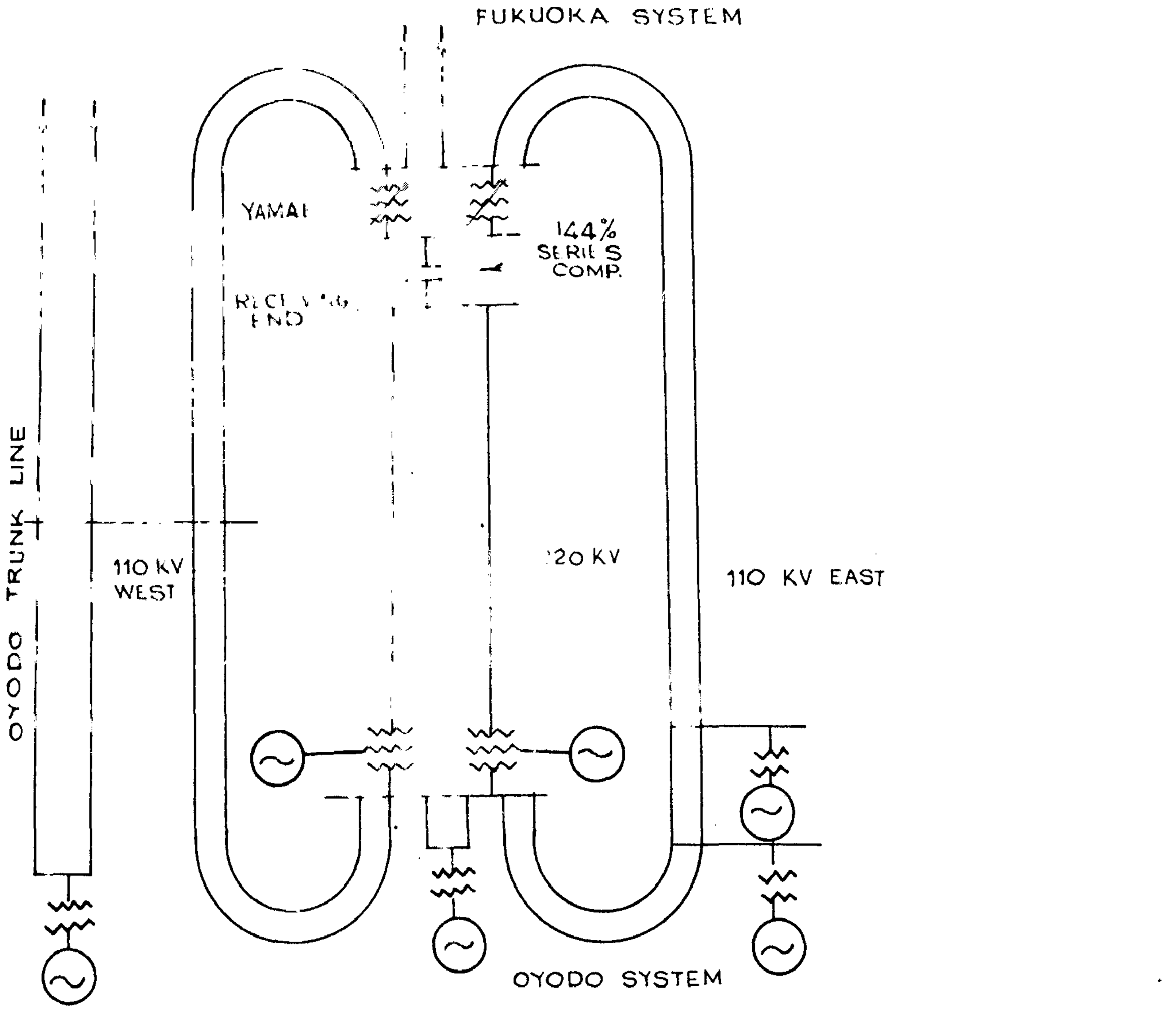


FIG 1.1. JAPANESE 220 & 110 KV LOOP SYSTEM

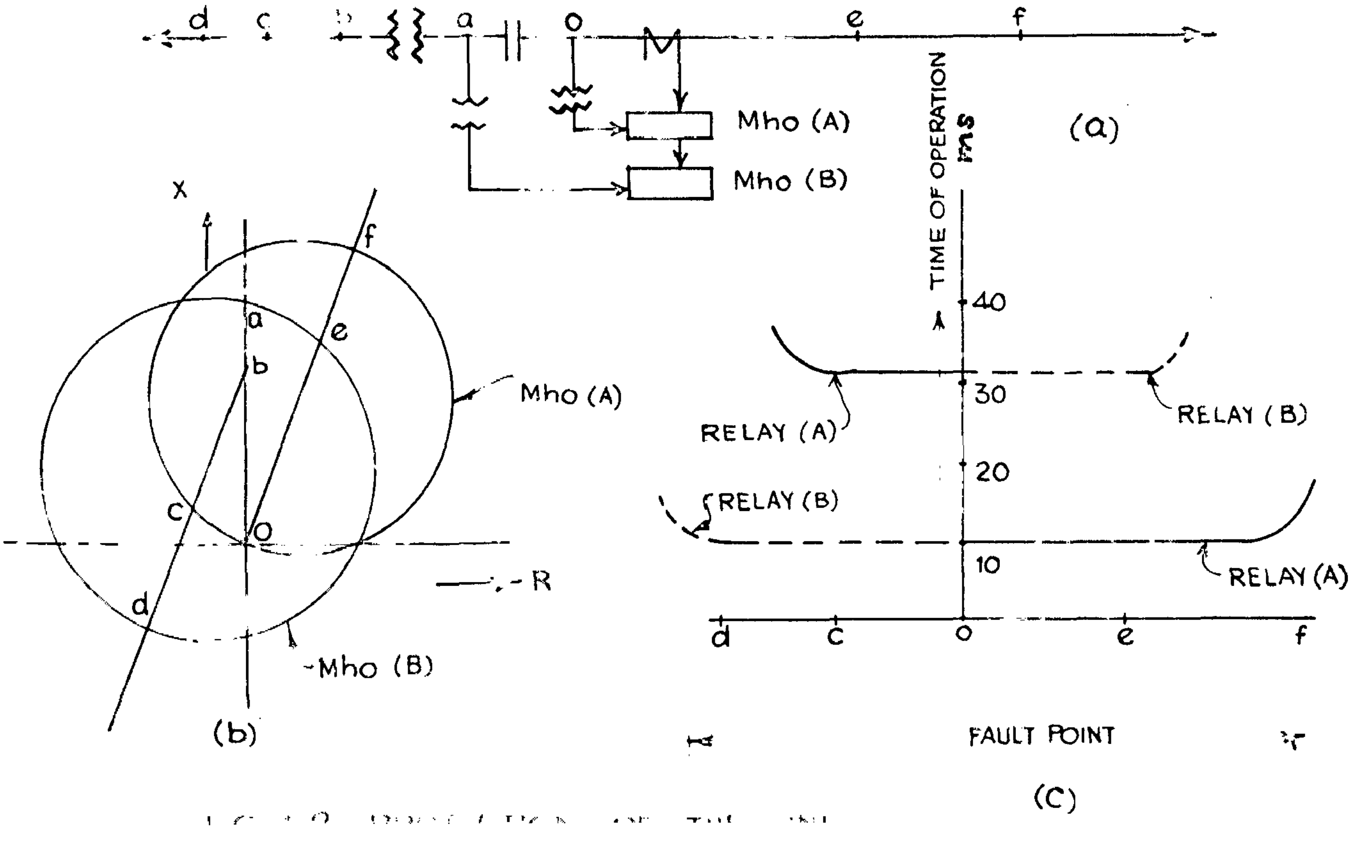


FIG 1.2 [illegible] OF THE [illegible]

Protection to the series capacitor is given with an air-blast shunt arrestor, which is set to operate at 2.6 times the normal voltage of the capacitor. The by-pass switch is designed to protect the shunt arrestor from burning due to excessive fault current if it persists for more than 8 cycles. No disturbance of any kind was experienced in the above scheme during the staged fault tests.

However, there were some relaying problems. When the capacitor was installed at the receiving end, the directional relay at that sub-station was found to give false operation for fault points a, b and c shown in Fig.(1.2a). To avoid this, mho relays with memory action were installed. The correct operation of the mho relay can be obtained by giving time delay to the relay operation as shown in Fig.(1.2c). The relay (B) operates about 20 ms ahead of relay (A) for fault occuring in the backward zone with reference to point 'O', whereas for forward fault relay (A) operates 20 ms ahead of relay (B). With the help of this time discrepancy of operation of relay (A) & (B), correct relaying has been obtained.

For 220KV main trunk line, carrier relay was used.

CHAPTER 2

LOCATION AND OPTIMUM COMPENSATION OF SERIES CAPACITOR

Another advantage ~~from~~ of placing the capacitor at the middle of the line, is that the fault current will be less, and hence the size of protective equipment for the series capacitor will be reduced.

Moreower, it has been found that due to wave formation in the line, the effective reactance of the capacitor is less than its rated value. However, the effective reactance of the series capacitor increases if it is placed at the centre instead of at the ends of the transmission line.

For double circuit line the capacitors can be placed at the busbars of the intermediate sub-stations or at the centre of the indivisual lines.

2.2. PERCENTAGE OF SERIES COMPENSATION:

The main purpose of using the series capacitor is to increase the transient stability limit of the line. In ideal case the amount of compensation will be such that transient stability limit approaches the most economical loading of the line. Therefore, the amount of compensation to be inserted for a particular system is decided by comparing the minimum cost of transmission of power for different percentage of compensation.

The transient stability limit of a series compensated line depends upon a number of important factors, such as type of system, type of assumed fault, percentage of transmission capacity removed when the faulted line section is cleared, time of breaker operation, time of short-circuiting the capacitor during the fault and reinsertion time of the capacitor after the clearance of fault.

S.B. Crary[15] has calculated the transient stability limit for double circuit line, for different locations of capacitors and

2.1. LOCATION OF SERIES CAPACITOR:

It has already been established that various benefits can be obtained by the use of series capacitors in the power system. The question of location and amount of line compensation arise automatically due to use of series capacitor in the system.

Due considerations about the operational and protective relaying necessiate insertion of large number of capacitors, having small capacity, uniformly along the line. But it is not practicable due to economical reasons.

Therefore for the single circuit line the series capacitors can be located at either of the three places, sending end, receiving end, or at the centre of the line.

1. Leading sending end and receiving end power factors result with the capacitor placed at the sending end.
2. Capacitor placed at the receiving end, gives rise to lagging sending end and receiving end power factors.
3. When the capacitor is placed at the centre of the line, the sending end and receiving end power factors lie somewhere between the values of (1) and (2).

As the leading power factors reduce the capability and steady-state stability of the synchronous generators and as most of the loads are lagging, the use of series capacitors at the sending end is not desirable.

In case the power flow is in one direction, the series capacitors can be placed at the receiving end, as it can operate at a lagging power factor.

But when power flow is in either directions, the best location for the series capacitor is obviously at the centre of the line.

different percentage of compensation. These values are expressed in per unit of surge impedance loading of line and it is quite general and can be used for any voltage rating.

2.3. COST ANALYSIS:

In view that 400KV tie line connecting interstate grids will come up very soon in India; and in some of those lines, series compensation may be necessary. Therefore the cost of transmission of power is calculated for different location and different percentage of series compensation, to find out the best location and optimum compensation of series capacitor under Indian condition.

The calculation is carried out as follows.

The four different methods of applying the series capacitors have been considered.

2.3.1. Method of Series Capacitor Arrangements:

Method 1: In this method the series capacitors are located in the buses of the intermediate stations. Here the capacitors are designed to carry the full load current. The over-voltage protection is provided with the help of spark gaps.

Method 2: In this method the series capacitors are located in the middle of the line sections. Sometimes this method is also used to balance the loading of the transmission lines.

Method 3: This method is similar to method no.1. The capacitors are located in the buses of the intermediate stations. There is a provision for switching off the part of series capacitors to increase the series capacitive reactance, in order to compensate a portion of the increased line reactance resulting from the disconnection of faulty line section.

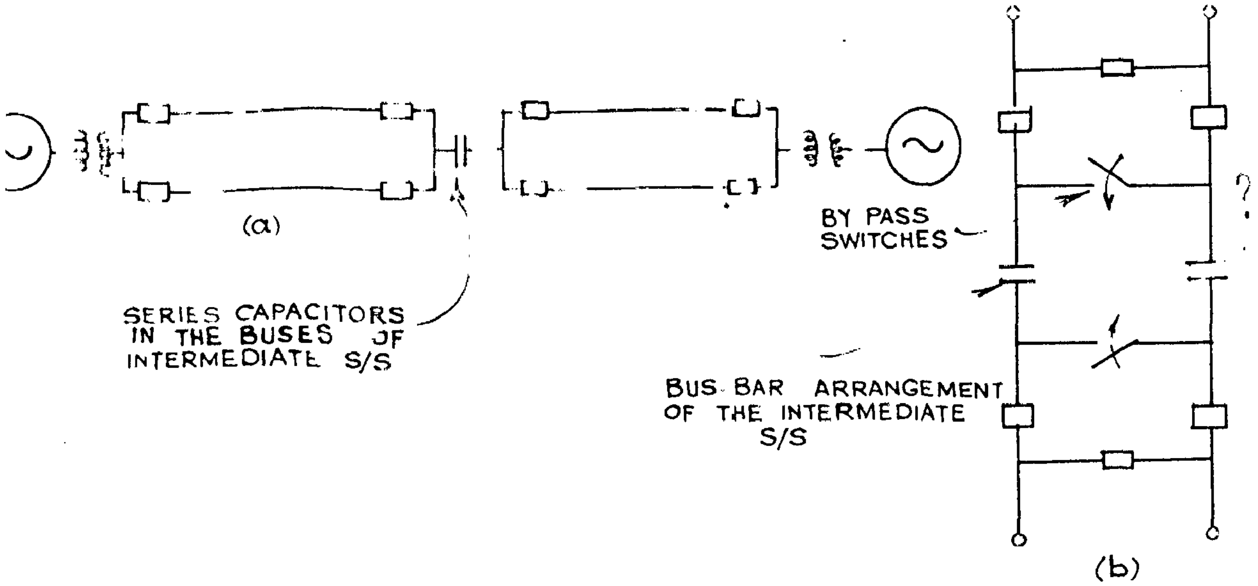


FIG. 2.1 METHOD NO. 1

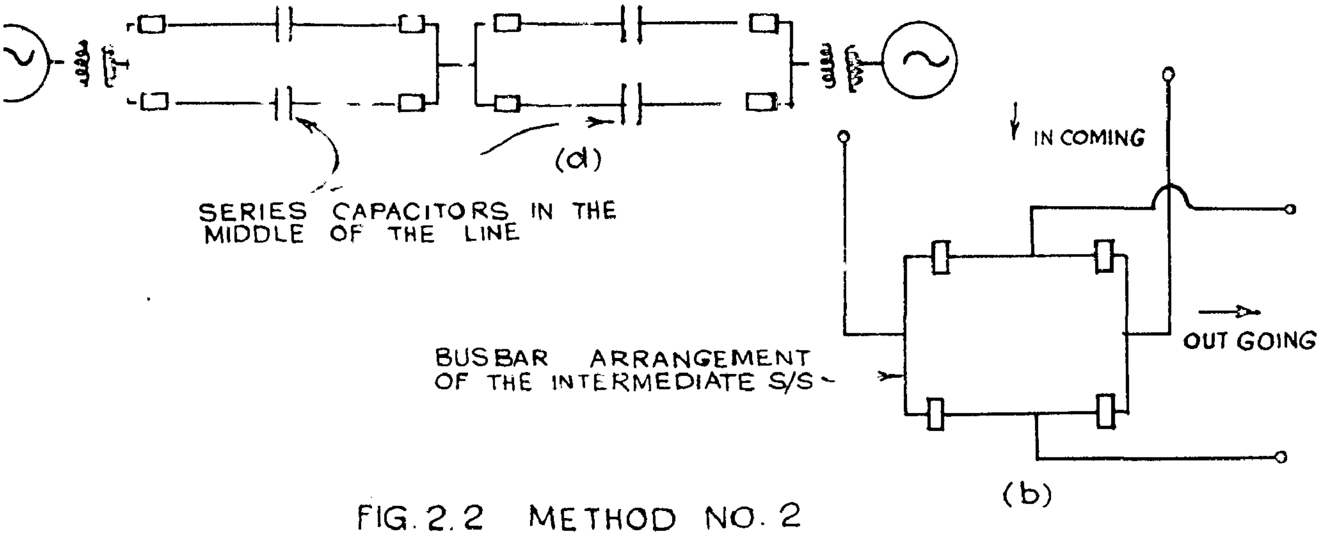


FIG. 2.2 METHOD NO. 2

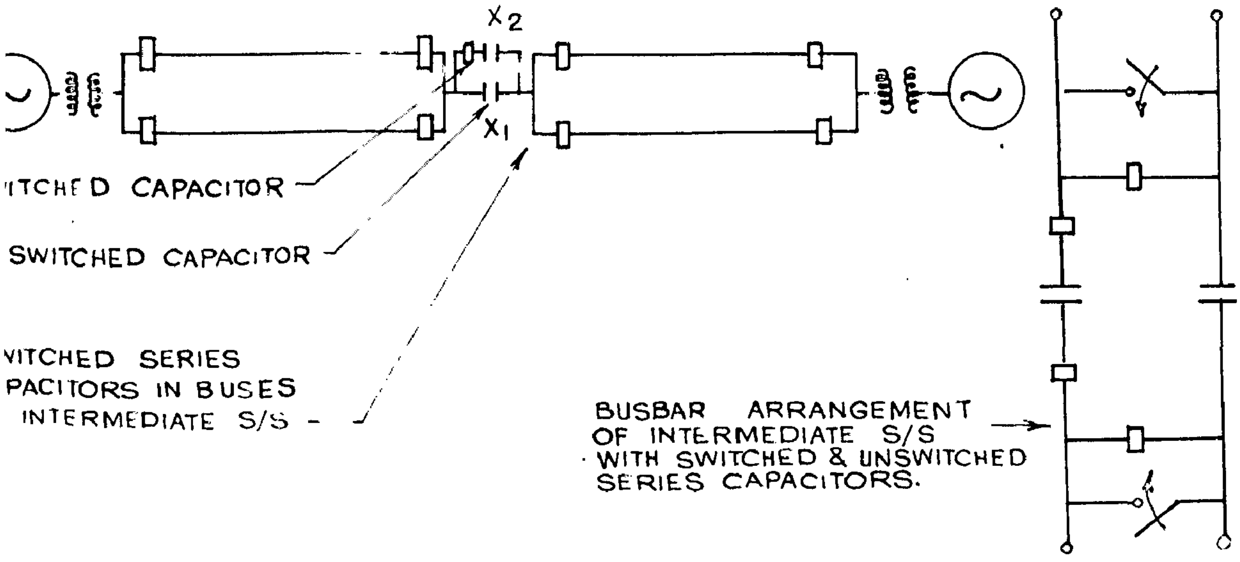


FIG. 2.3 METHOD NO. 3.

<u>Method 4:</u> This is a combination of method 1 and 2. A part of the series capacitors is installed in bus-bars of intermediate stations and the other part is in the line sections. The capacitors in the intermediate station buses are required to carry the continuous full-load current, while the capacitors in the each line sections carry the continuous full-load current when one parallel line section is switched out.

Table No.2.1 shows the transfer reactance of the series capacitor compensated line for the different arrangements of the series capacitors.

<u>TABLE No.2.1</u>

Method of arrange-ment of series capacitors	Transfer impedance		Change in Transfer reactance	Total series capacitor rating.
	All lines are in service	One line section is switched out		
1	$\frac{n}{2}(1-K)X_L$	$\frac{n}{2}(1-K)X_L + \frac{X_L}{2}$	$X_L/2$	$\frac{K.n}{2} I^2.X_L$
2	$\frac{n}{2}(1-K)X_L$	$(\frac{n+1}{2})(1-K)X_L$	$\frac{X_L}{2}(1-K)$	$2K.nI^2X_L$
3	$\frac{n}{2}(1-K)X_L$	$\frac{X_L}{2}(1+n(1-K)) - \frac{X_1^2}{X_1+X_2}$	$\frac{X_L}{2} - \frac{X_1^2}{X_1+X_2}$	$(n-1)I^2X_1 + \frac{I^2X_1^2X_2(n-1)}{(X_1+X_2)^2}$
4	$\frac{n}{2}(1-K)X_L$	$(\frac{n+1}{2})(1-K)X_L - X_LK''$	$\frac{X_L}{2}(1-K) - X_LK''$	$nI^2(2K-K'')X_L$

Where,

n = number of equal length of line section in series.

K = degree of compensation.

$= \frac{\text{Series Capacitor reactance}}{\text{Total line reactance}}$

K" = Degree of compensation by the capacitors located in intermediate bus for method 4.

X_L = Reactance of the line section

X_1,X_2= Reactance of Capacitor for method 3.

From the Table 2.1 it is obvious that the change in transfer reactance in case of method 2 is less than that of method 1. However, the rating of the series capacitors for method 2 is 4 times than that of method 1. In method 3 by making suitable adjustment of X_1 and X_2 the change in transfer reactance can be made zero. In method 4 the change in transfer reactance can be reduced by keeping a part of series capacitor in the line.

2.3.2. Economic Assumptions:

A 400KV, double circuit bundle conductor line of 480 miles in length as shown in the Fig.(2.5) has been chosen. Other detailed specifications are given in Appendix 1.

Cost datas for 400KV line as obtained from C.W.P.C., is also given in Appendix 1.

The transient stability limit for different methods and different percentage of compensation is obtained from reference 15, the values of which are tabulated in Appendix 1.

With this cost datas and transient stability limit, the cost of transmission of electrical energy has been calculated. In Table No.A.1.5 to A.1.8, the cost of transmission per unit of energy has been given. The curves showing percentage of series compensation versus cost of transmission of energy are plotted in Fig.(2.6) to (2.9).

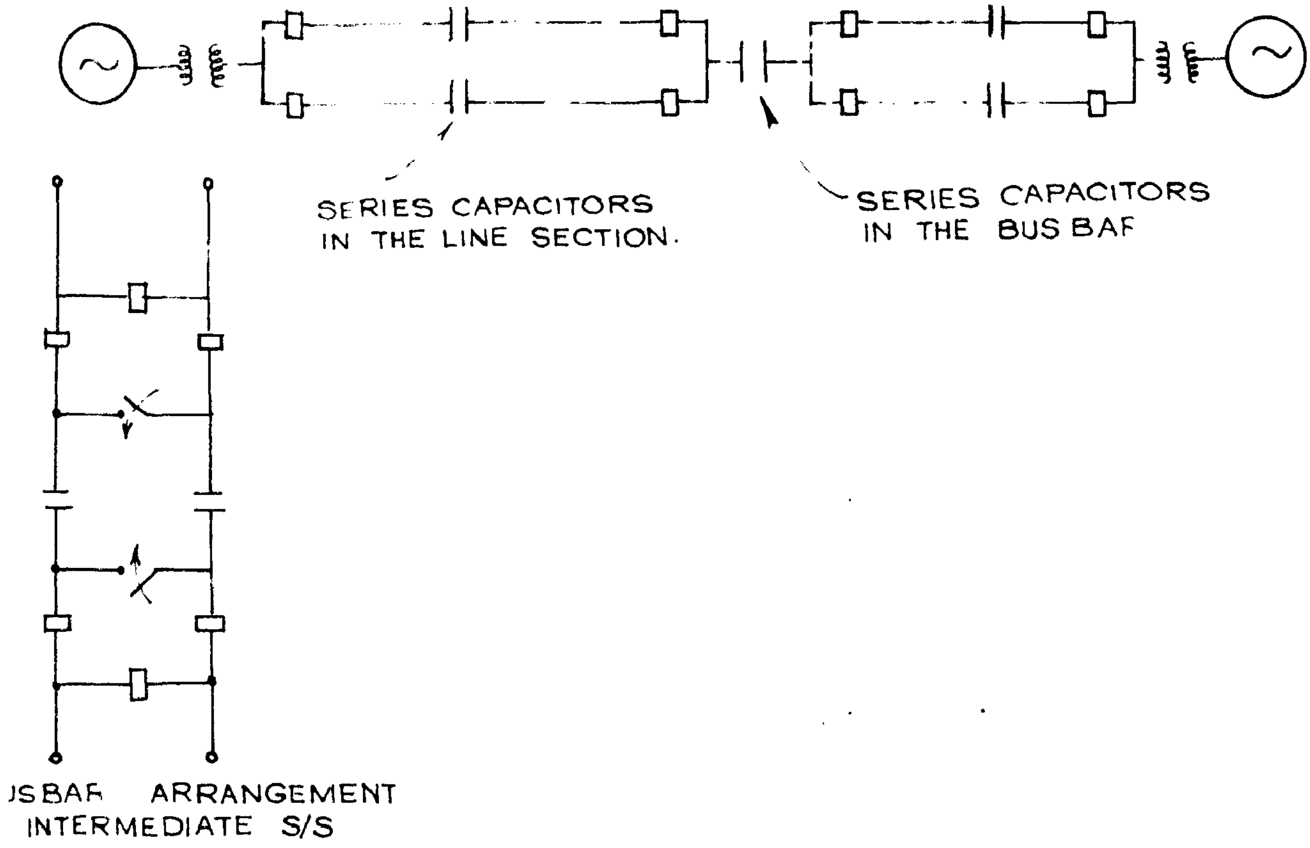
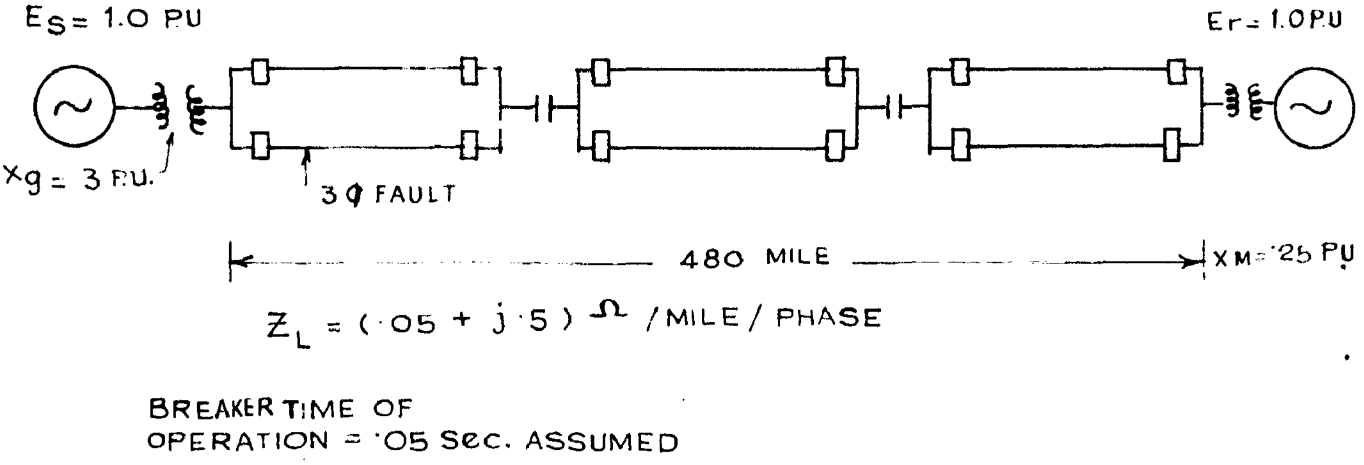


FIG. 2.4 METHOD NO. 4.



i. 2.5 400 KV BUNDLE - CONDUCTOR LINE.

2.3.3. Inferences:

1. In Fig.(2.6) to (2.9) it is seen that the cost of transmission per unit of electrical energy decreases with the introduction of series compensation. The reason is mainly due to decrease of annual charge of transmission line. But after certain percentage of compensation the cost again increases because the cost of series capacitor and the line loss increases more rapidly.

2. From the graphs it is obvious that method 1 gives the most economical arrangement of series capacitor. In the method 1, the cost of transmission of energy becomes minimum with three intermediate substations and 45% series compensation.

However, the above method with one intermediate substation and 60% of series compensation is equally attractive from the economical point of view. But for purpose of maintenance more numbers of intermediate sub-stations are desirable.

The method 3 provides the second best arrangement of series capacitor. With 12.5% of initial compensation and 100% of excess reactance compensation, the minimum cost of transmission may be obtained by method 3. However, the complicacy of switching arrangement makes this method unsuitable.

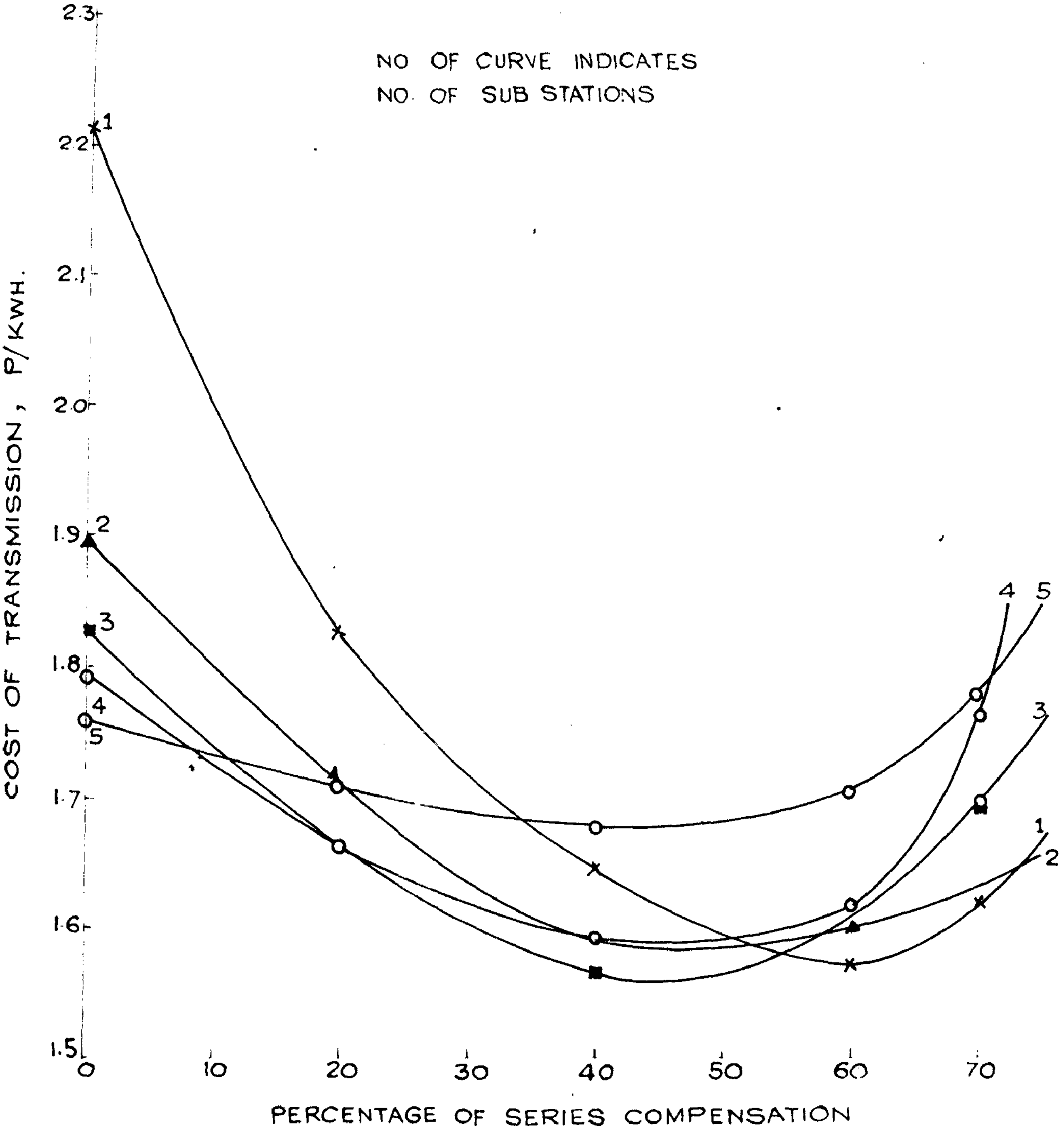


FIG. 2.6

METHOD 1. SERIES CAPACITORS IN THE INTERMEDIATE-SUB-STATION.

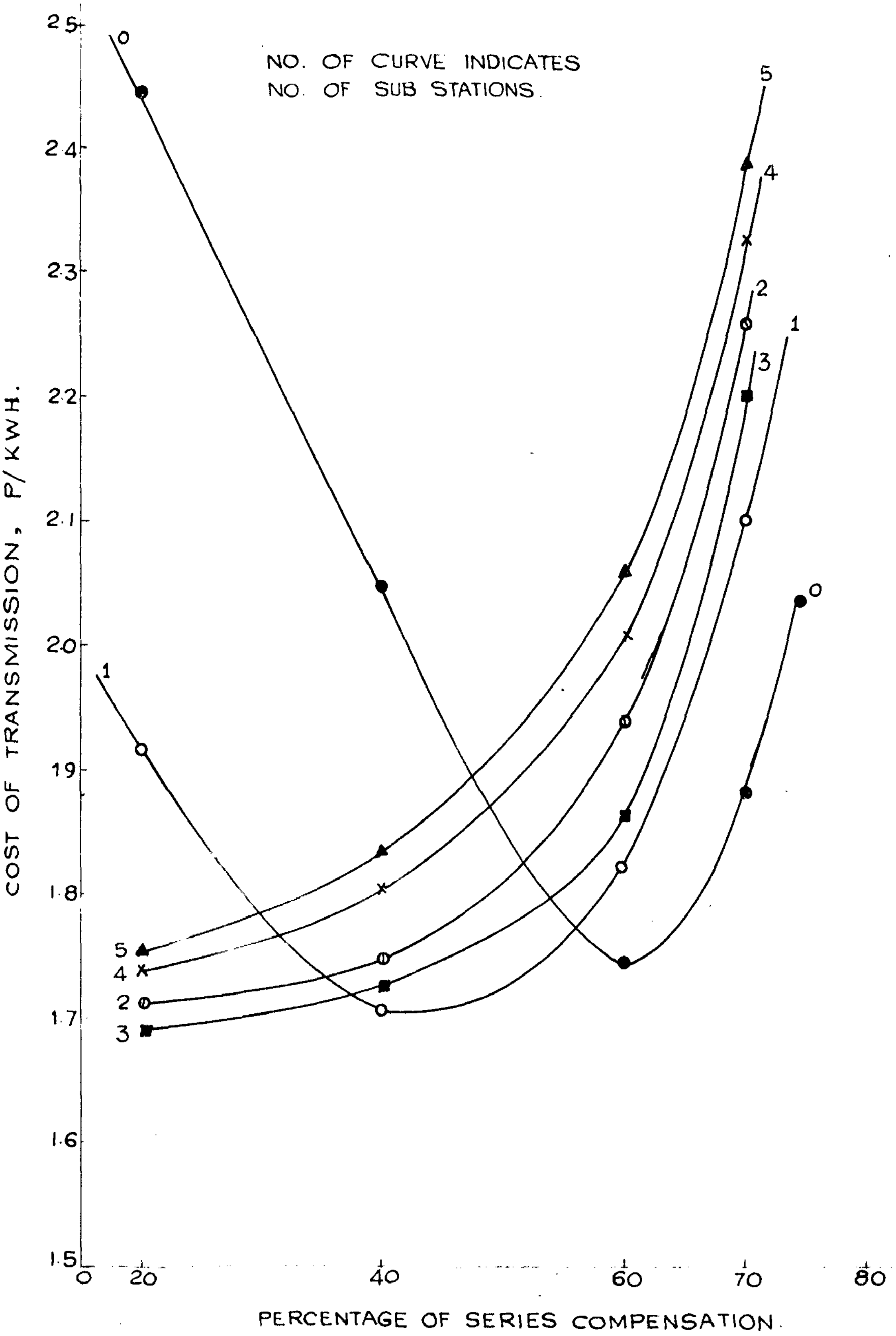


FIG. 2.7

METHOD 2. SERIES CAPACITORS IN THE MIDDLE OF THE LINE

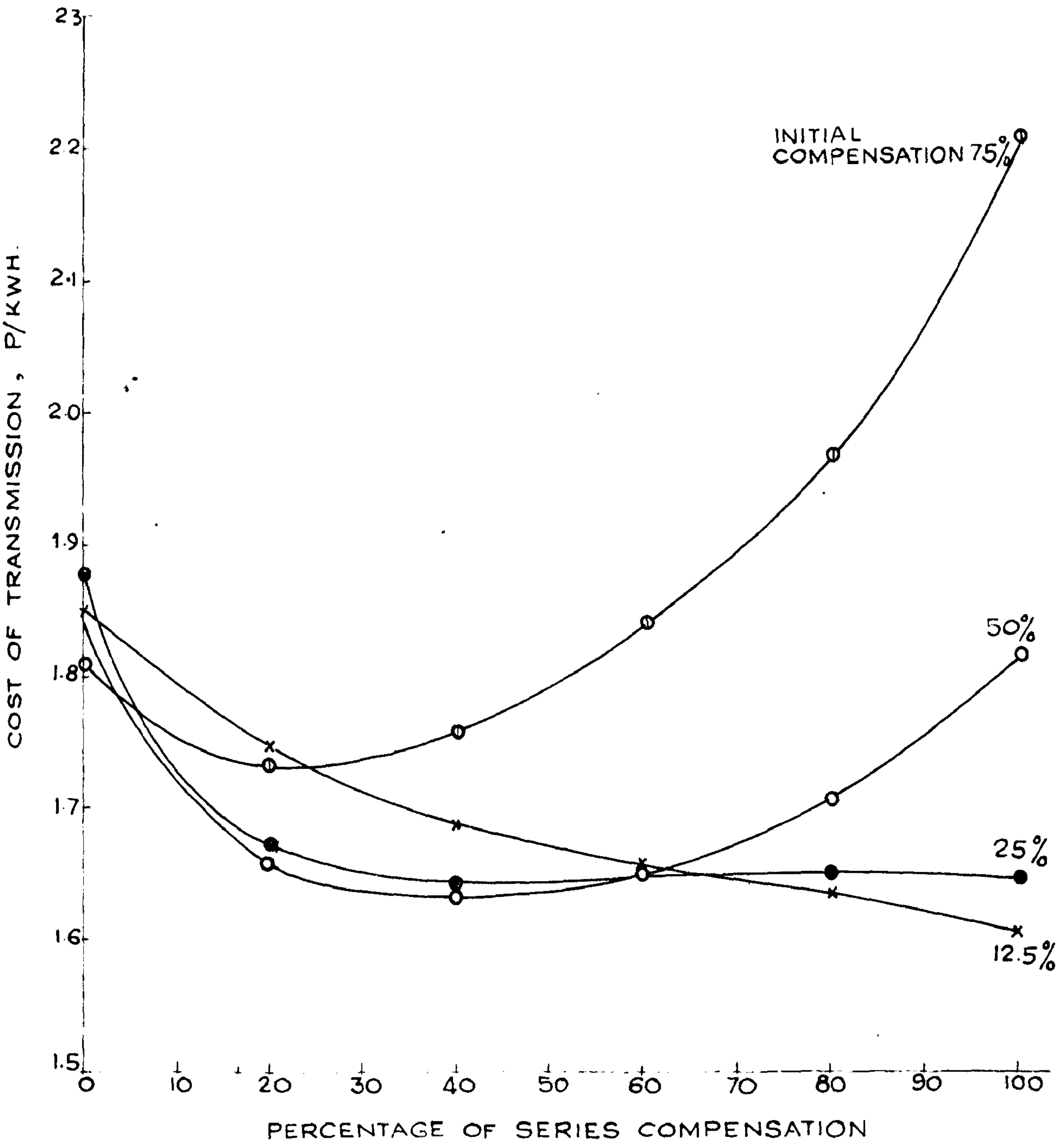


FIG. 2.8

METHOD 3. 3-INTERMEDIATE SUB-STATION IS CONSIDERED

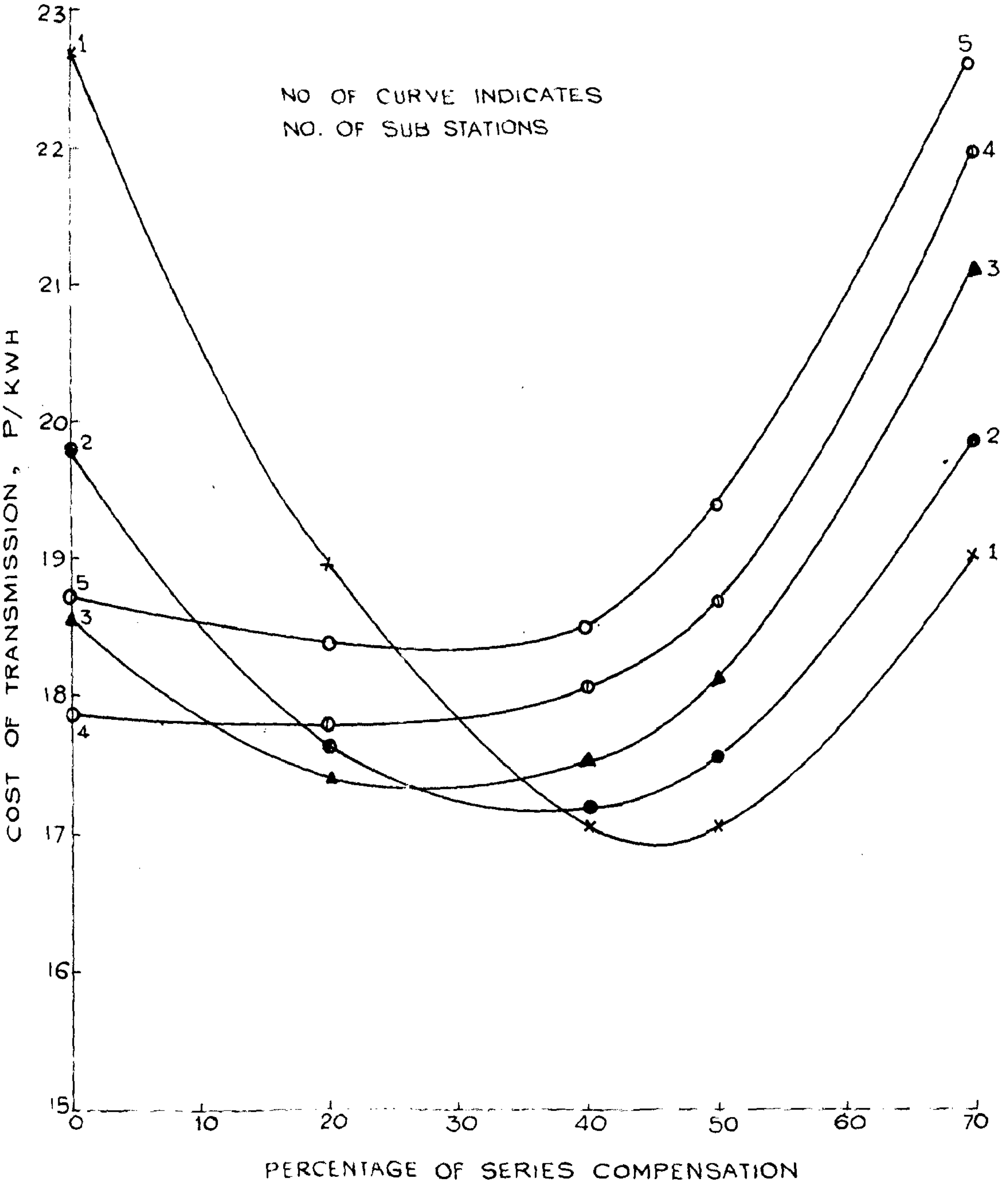


FIG. 2.9

METHOD 4. 30% COMPENSATION IN THE BUS BAR IS ASSUMED

CHAPTER 3

PROTECTION OF SERIES CAPACITOR

3.1.2. Maximum Momentary Line Current:

This should not exceed 150% of maximum continuous working current of the capacitor and the spark gap should not operate under such condition.

3.1.3. Maximum Fault Current and its Duration:

The expected maximum fault current and its duration is to be considered in designing the spark gaps, particularly the current limiting resistor connected in series with the spark gaps.

3.2. OVER VOLTAGE PROTECTION OF SERIES CAPACITOR:

Voltage across the capacitor increases with the increase of current flowing through the capacitor due to fault. As the capacitors are designed only to withs and 2½ times the rated voltage, there must be some devices to protect the capacitor from the damage due to over voltage. The protection of the series capacitor can be given by the spark gaps in series with resistors, connected across the capacitors. The gap shown in the Fig.(3.1) breaks down when the voltage across the capacitor exceeds 2½ times the capacitor's rated voltage. The resistor in series with the gap is designed to limit the discharge current of the capacitor to allow the repetitive break-down of the gap without damaging the capacitor. It has alread been mentioned that after the clearance of the fault, the series capacitor should be reinserted to the circuit as rapidly as possible. This is accomplished by designing the special gap in such a manner that it will be subjected to constant air blast during the period of flow of current. As a result the arc becomes unstable and it clears at each current zero. Thus the gap restrikes on each half cycle and is extinguished at each current zero so long as the line current is 250% or more of the normal value.. When the short circuit is removed by a high speed relay and circuit breaker, the line current again becomes the normal value and the gap ceases to operate.

The air blast across the gap is initiated by the gap current. When the gap current ceases to flow the solenoid holding the air valve open, gets de-energised and closes the air valve. A time delay is given to the operation of the air valves, so that sufficient air continues to flow to complete the de-energisation of the gap to restore the gap insulation level fully.

3.3. OVER LOAD PROTECTION: > [illegible] [illegible]

Over load protection is necessary for the series capacitor, because it is not desirable to operate the capacitor continuously above the predetermined value due to thermal reasons. The capacitor may be operated continuously at the rated voltage plus 5% corresponding to the standard practice. It may be allowed to operate for 30 minutes at 135% and 5 minutes at 150% normal voltage. Therefore some mechanism has to be developed to operate the capacitors below this limit.

An inverse time relay is installed to detect the overvoltage across the series capacitor through a potential transformer. This relay operates the by-pass switch to shunt the series capacitor. Once the by-pass switch is closed it has to be reset manually. This by-pass switch is a high-voltage indoor single-pole switch arranged to remain closed by spring pressure and to be opened by air pressure. The normal supply of the air in the air blast reservoir keeps the switch in the open position. By shutting off the air supply from the cylinders the switch is made to close. Some times the voltmeter is also used to measure the voltage across the series capacitor. The arrangement is shown in Fig.(3.2).

3.4. OVER VOLTAGE DUE TO FUSE OPERATION:

If several capacitors are disconnected from the group due to

3.1. INTRODUCTION:

Series capacitors used in transmission limes are protected from excessive over voltages which appear across it during faults in transmission line, by the spark gaps connected parallel to the capacitors. It is not economical to design a capacitor to withstand an over voltage more than 2½ times its normal rating.

So the spark gap's break-down voltage is set at 2½ times the normal rating of the capacitor. To obtain the maximum use of the series capacitor compensation of the line reactance, capacitor should be short circuited only during the fault period, and to be reinserted immediately after the clearance of the fault. Another requirement of the series capacitor protective device, is that it should not operate when the line is energised again after it has been de-energised even for a few cycles. With this type of protective device, the series capacitor can be designed on the basis of maximum continuous current, and it allows a relatively close protection level. This close protective level does not affect the transient stability of the system, as the protective device operates only during the period of excessive fault current.

In designing the protective device for the series capacitors, the following factors have to be given due consideration.

3.1.1. Maximum Continuous Line Current:

It is the maximum continuous current which is expected to be present in the line to supply the maximum demand. This line current multiplied by the reactance will give the voltage rating of the capacitor, and the product of the current squared and the reactance will give the KVAr rating of the capacitor.

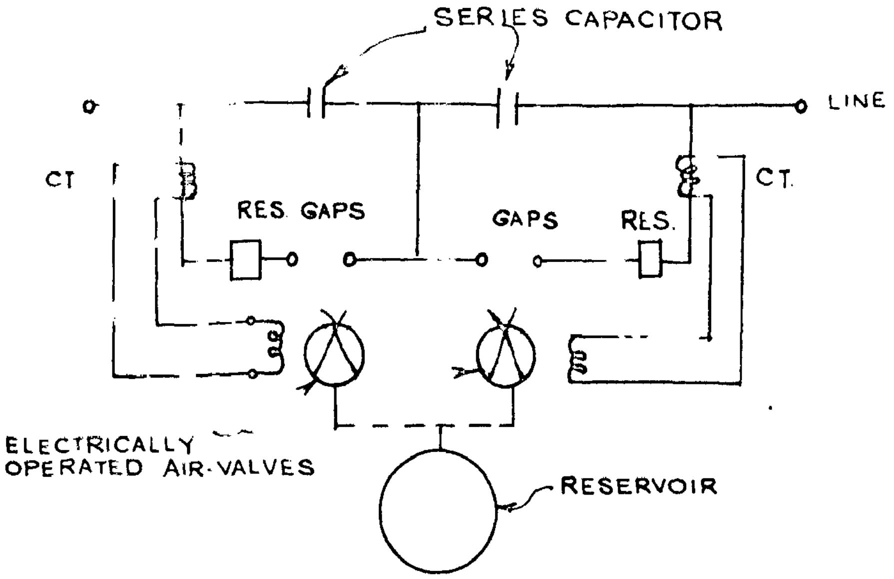


FIG. 3.1 SPARK GAP ARRANGEMENT

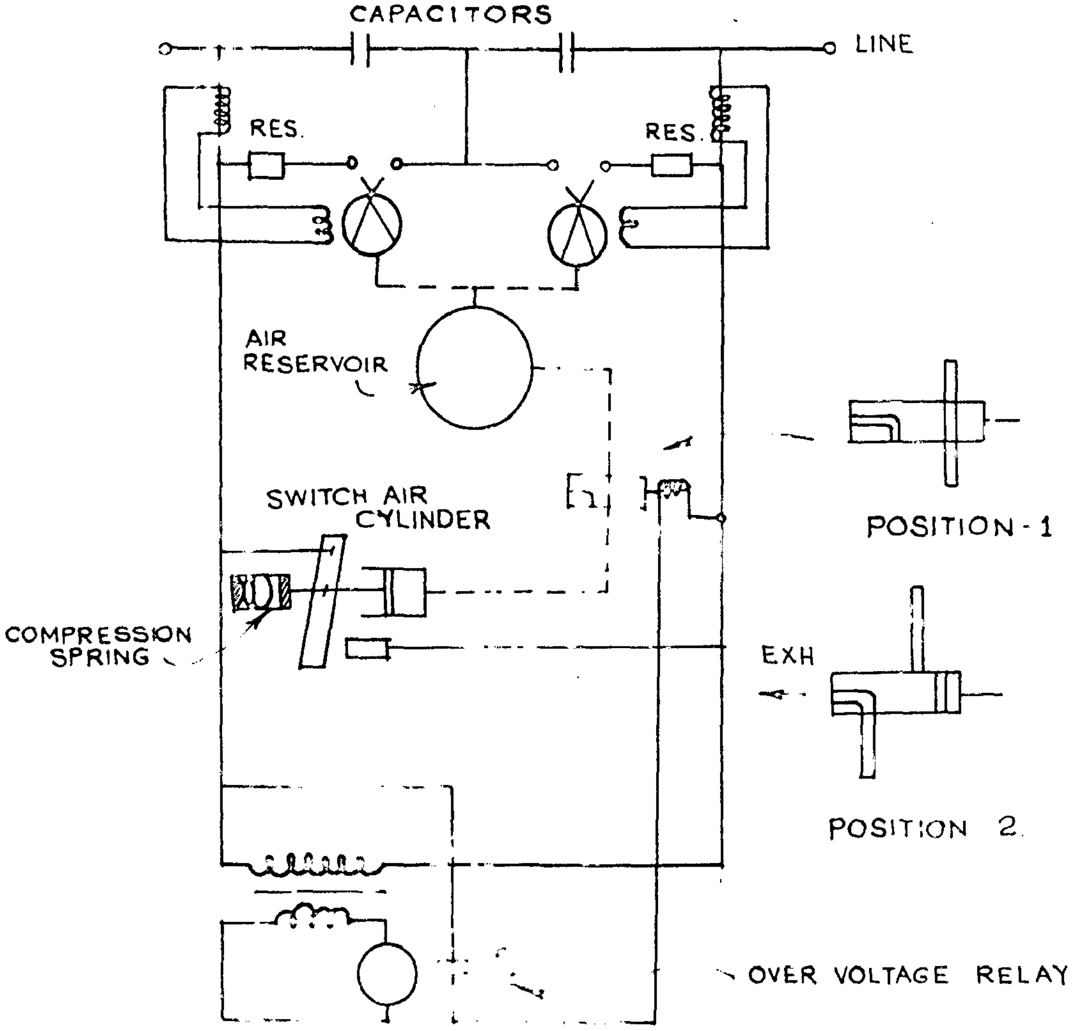


FIG. 3 2 BY PASS SWITCH ARRANGEMENT

blowing of the fuses, the remaining capacitors will be subjected to higher voltage owing to increase of reactance of the group.

This problem is solved by dividing the capacitors in two equal branches as shown in Fig.(3.3). The differential relays are used to compare the current in each branches of capacitors and it operates the air valves which in turn close the by-pass switch.

The closed position of the by-pass switch is indicated at ground level by the pneumatically operated relays located at the compressor stations.

3.5. COMPRESSED AIR GAP:

Diagram of the compressed air gap in shown in Fig.(3.4). It consists of an inverted electrode of special graphite, fitted inside a porcelain insulation. The second electrode also made of graphite, lies along the axis of insulator, which forms a gap in the cavity of this inverted cup electrode.

The current flowing through the gap, during its break-down, opens the air valve, as a result air flows to the bottom chamber from which it goes to the porcelain tubular insulating body, and comes out through the passage in the central electrode as shown in the Fig.(3.4).

3.6. OTHER PROTECTIVE FEATURES:

The other protective features are, the provision for the automatic closing of the by-pass switch in the event of loss of air in the reservoir, or the prolonged arcing of the gaps due to inadequate air supply or the failure of air valve to open.

A grounding switch is provided to drain way any static charge which may be formed on the platform and on the housing of the series capacitors.

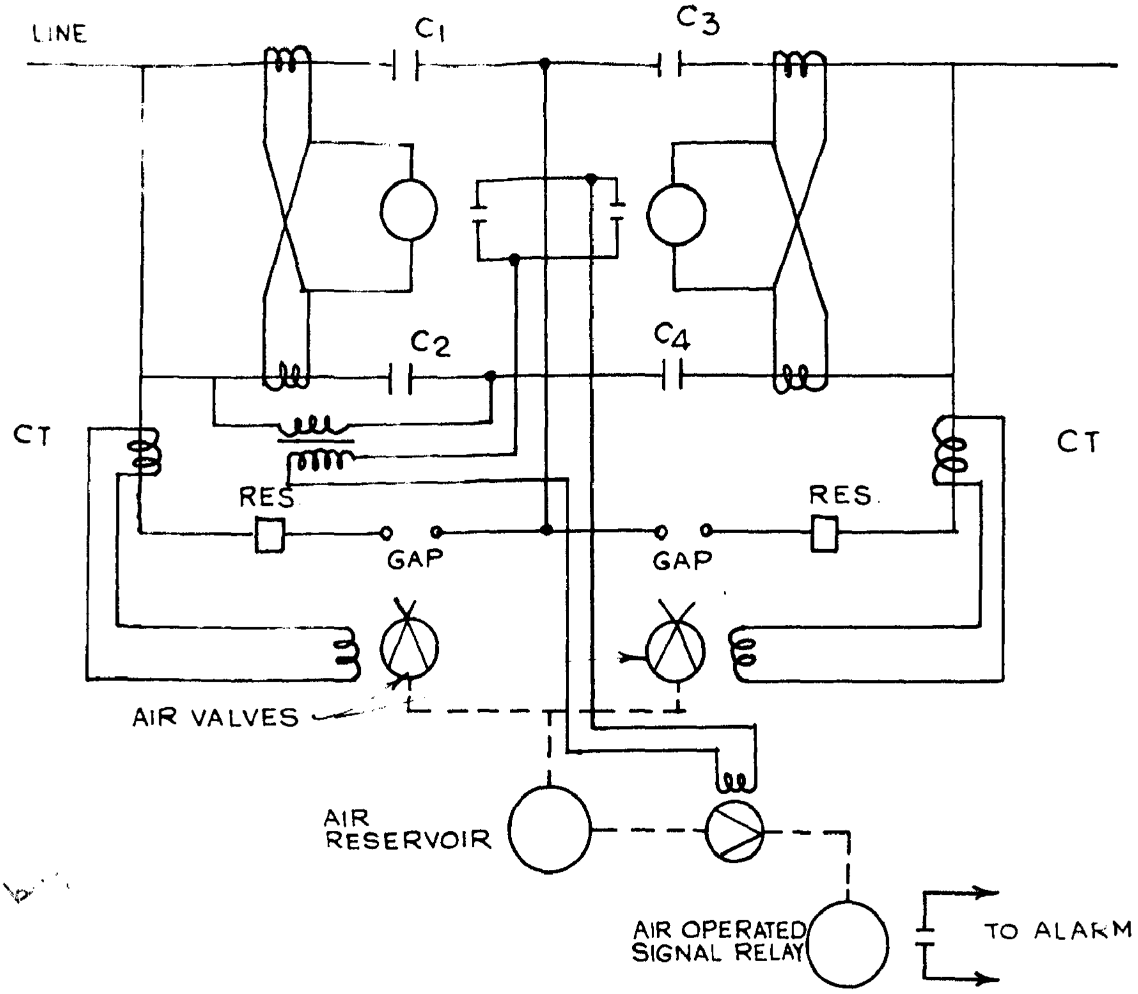


FIG. 3.3 FUSE INDICATING DEVICE

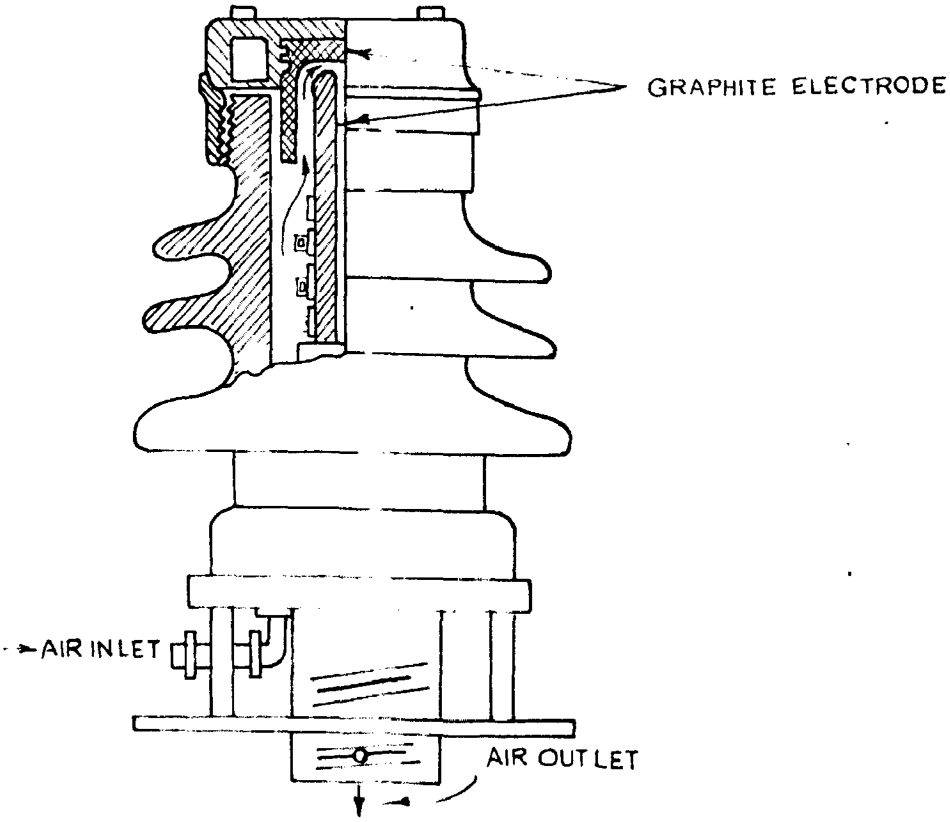


FIG. 3.4 SPARK GAP

3.7. GAP OPERATION TIME:

The spark gap operation time has an important effect on the operation of relays for the transmission line.

The time of operation of the spark gap depends upon the time required by the fault current to attain the maximum value. The surface of conduction of the spark gap is given a spherical shape so that for the power frequency voltage it will cause break-down exactly at the voltage for which it has been set. The maximum time required by the fault current to reach the peak value is ¼th of a cycle and therefore the gap will operate in ¼th of a cycle.

It has been experimentally verified by E.L. Harder[10] that time of operation of the gap is ¼th of a cycle if the fault current exceeds 2½ times its normal value, when the spark gap's break-down voltage is set at 2½ times the normal voltage rating of the capacitor.

CHAPTER 4

ANALYSIS OF SERIES COMPENSATED CIRCUIT

4.1. INTRODUCTION:

The series capacitors used in transmission lines, affect the operation of Distance and Carrier relays which are most commonly used for the protection of high voltage transmission lines. The behaviour of above relays in a compensated line, depends upon the degree of compensation and the location of the series capacitors.

In this Chapter the analysis of the operation of different types of relays used in compensated lines will be discussed.

4.2. EFFECT OF SERIES CAPACITOR ON DIRECTIONAL ELEMENT OF DISTANCE RELAY:

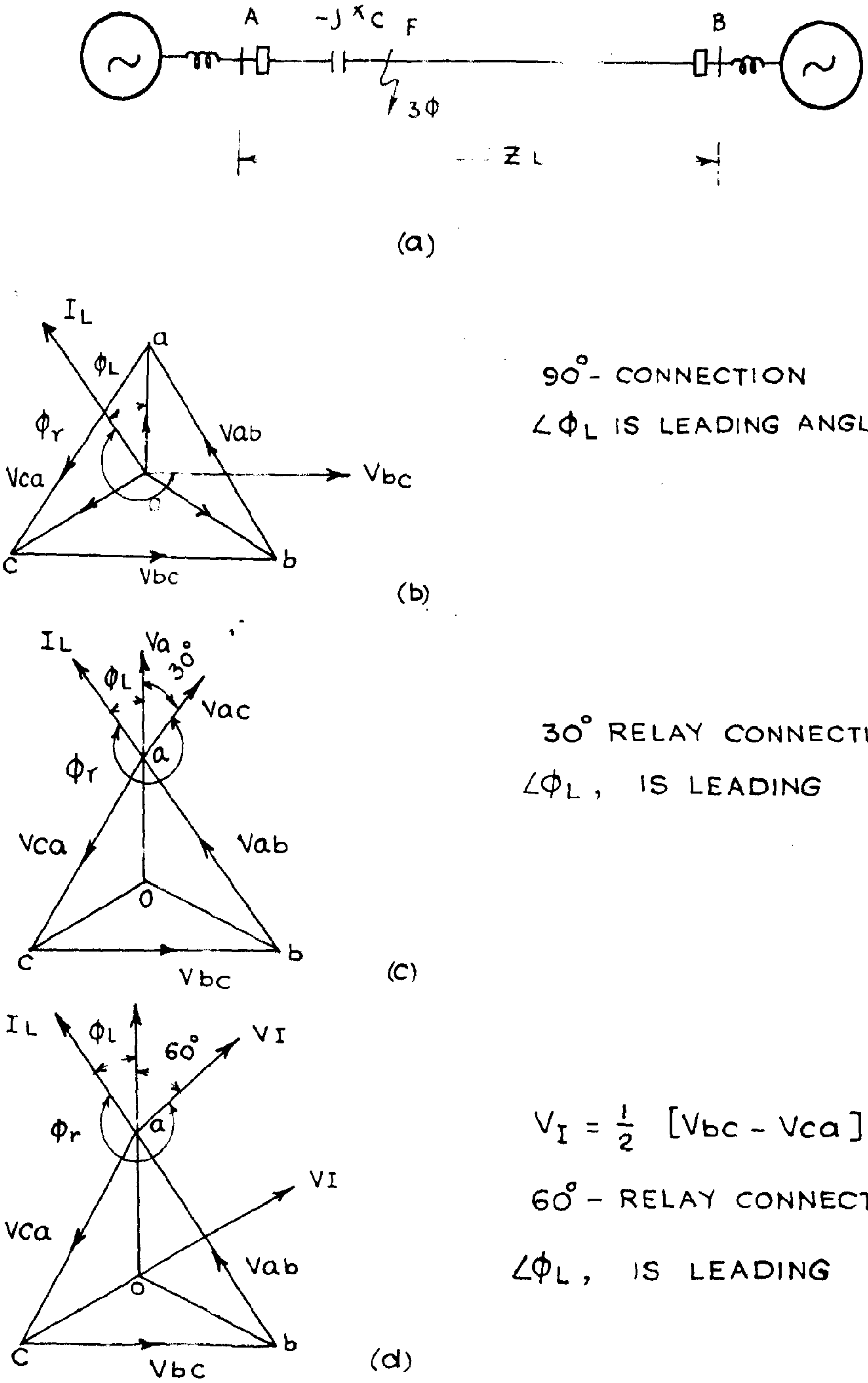
To study the effect of series compensation on the directional element of the Distance relay, a system as shown in Fig.(4.1) may be considered. The capacitor is located near the busbar A and a 3 phase fault occurs at F. It is assumed that the reactance of the series capacitor is greater than the reactance of the line from fault point F to bus A, i.e. $|X_C| > |X_{af}|$. Under this condition directional relay located at A will not operate correctly due to capacitive fault. But directional relay at B will operate correctly as the fault point appears to the relay as inductive. The operation of directional relay due to capacitive fault can be analysed as follows.

For the directional relay 90° connection may be assumed. As shown in Fig.(4.2b) for the relay at Bus-bar A, the fault current I_L will lead the phase voltage V_a by angle ϕ_L which is given by $\tan^{-1}\frac{X_C-X_{af}}{r_f}$, where X_C is the series capacitive reactance and $r_f + jX_{af}$ is impedance of the line, from F to A.

Torque developed in the relay is given by equation (4.1).

$$T = K' V_{bc}.I_L \cos(\phi_r + \alpha) \qquad \ldots \qquad (4.1)$$

where,



90° - CONNECTION

∠ϕ_L IS LEADING ANGLE

30° RELAY CONNECTION

∠ϕ_L, IS LEADING

$V_I = \frac{1}{2}\left[V_{bc} - V_{ca}\right]$

60° - RELAY CONNECTION

∠ϕ_L, IS LEADING

FIG. 4 1 VECTOR DIAGRAM OF DIRECTIONAL RELAY, FOR CAPACITIVE FAULT CURRENT.

where,

K' = Relay constant

V_{bc} = Voltage applied to the pressure coil of the relay.

I_L = Fault current at the relay terminal.

ϕ_r = Angle between I_L and V_{bc}

α = Relay angle.

By putting the value of ϕ_r equation (4.1) can be obtained as,

$$T = K' V_{bc} \cdot I_L \cos (90 + \phi_L - \alpha) \quad \ldots \quad (4.2)$$

(i) Now if $\alpha = 30^\circ$

$$T = K' V_{bc} \cdot I_L \cos (90 + \phi_L - 30)$$

$$= K' \cdot V_{bc} \cdot I_L \cos (60 + \phi_L)$$

$$\therefore T = 0 \text{ or } -ve.$$

for $-150^\circ \leqslant \phi_L \geqslant 30^\circ$

Therefore, for capacitive fault directional relay will not operate correctly when the fault current leads the voltage by more than 30°.

However by changing the values of α in equation (4.2) relay can be made to operate for different angles of fault currents, as shown below.

(ii) if $\alpha = 60^\circ$

$$T = K' \cdot V_{bc} I_L \cos (90 + \phi_L - 60)$$

$$= K' \cdot V_{bc} I_L \cos (30 + \phi_L)$$

$$\therefore T = 0 \text{ or } -ve.$$

For $-120^\circ \leqslant \phi_L \geqslant 60^\circ$.

(iii) if $\alpha = 90^\circ$

$$T = K' V_{bc} I_L \cos (90 + \phi_L - 90)$$

$= K'.V_{bc}\ I_L \cos(\emptyset_L)$

Therefore $T = 0$ or -ve

for $-90^\circ \ll \emptyset_L \gg 90^\circ$

The above analysis shows that the directional relay will operate correctly for the angle of the fault current laying between ±90°, if the internal angle of the relay is 90°.

Similar analysis is carried out for the directional relay with 30° and 60° connection in Appendix 2.

From these analysis it is observed that for 30° and 60° relay connections, the correct relay operation can be achieved, even if the angle of the fault current lies between ± 90°, and for that the internal relay angle should be 30° and 60° respectively.

4.3. EFFECT ON MHO RELAY:

The effect of series capacitors on mho relay can be seen by plotting the impedance of the line and the relay characteristics on impedance plane.

4.3.1. For Tie line without Intermediate sub-station:

For tie lines connecting two machines the series capacitor can be placed at any position.

The points 0, 1, 2, 3, 4 are the location of series capacitor at a distance 0, 25%, 50%, 75% and 100% from terminal A as shown in Fig.(4.2b). Fig.(4.2b) indicates that if the capacitor is located at a distance of 25% from terminal A, the series compensation should not be exceeded by more than 25%. Otherwise a portion of the line will remain outside the protected zone. That is with the conventional mho relay protective schemes, if the capacitor is located at a distance x from the sending end, the line compensation should

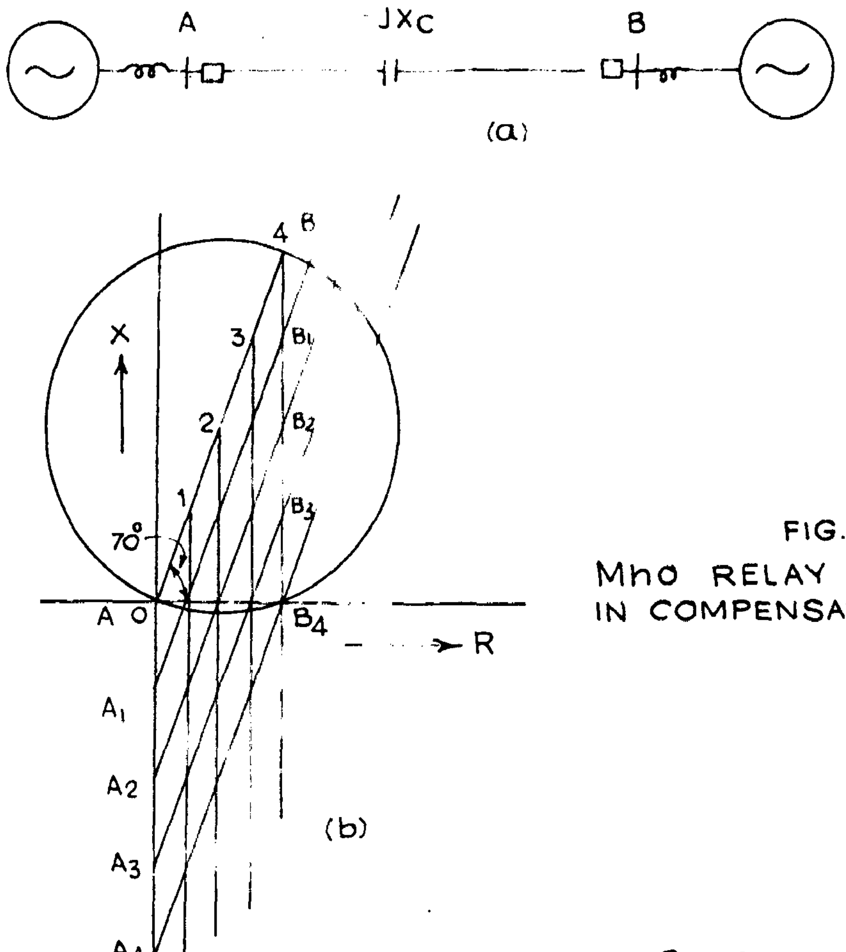


FIG. 4 2
MhO RELAY CHARACTERISTIC IN COMPENSATED LINE

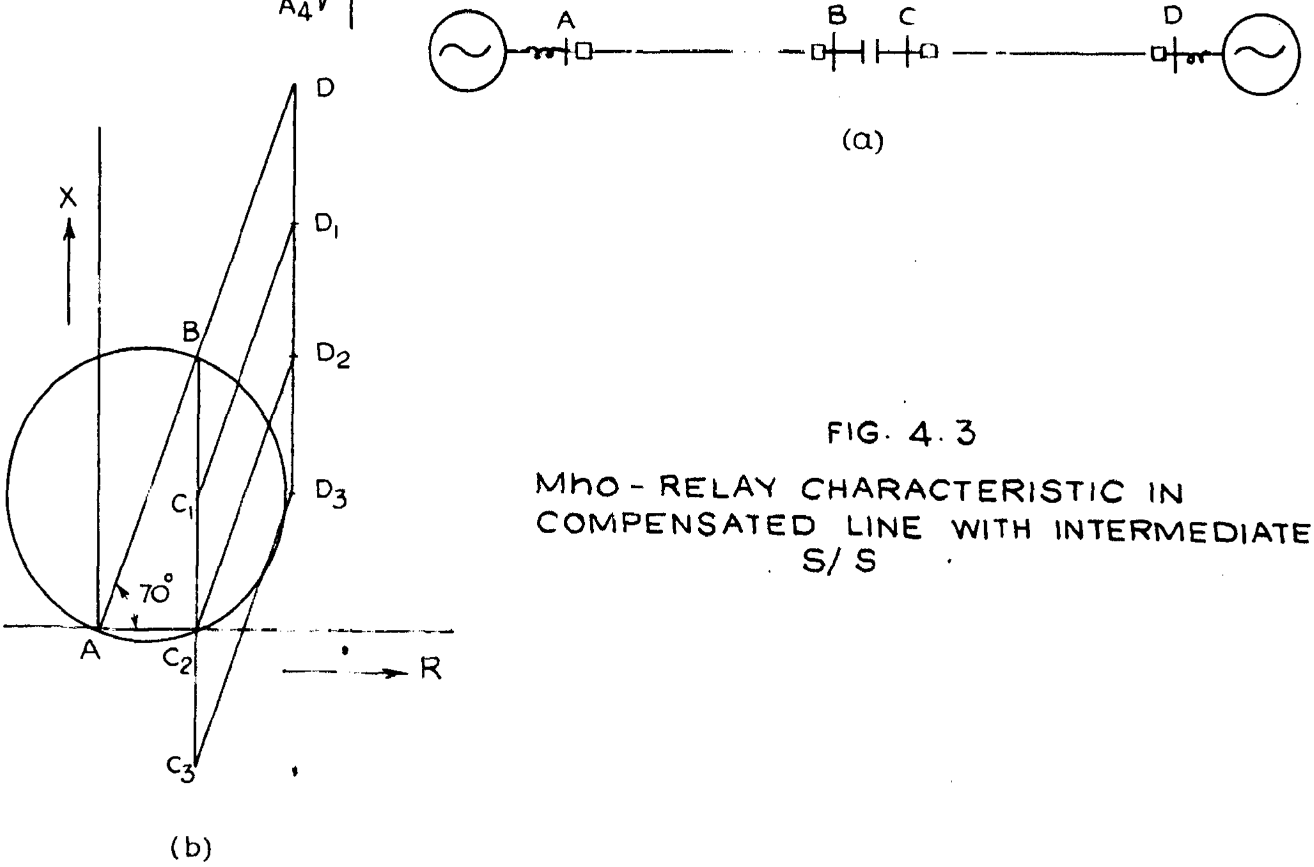


FIG. 4.3

MhO - RELAY CHARACTERISTIC IN COMPENSATED LINE WITH INTERMEDIATE S/S not be exceeded by x%.

4.3.2. For Tie line with Intermediate Sub-station:

The series capacitors can be located at the bus-bars of the intermediate sub-station as shown in Fig.(4.3a).

In Fig.(4.3b), ABC_1D_1, ABC_2D_2, and ABC_3D_3 are the line impedances with 25%, 50% and 75% series compensation. From the same diagram it is seen that the first zone of mho relay at A for the section AB, will over-reach for the external faults due to presence of capacitor in intermediate busbar. However if the capacitor is shorted by the spark gaps, during the external faults, the relay will operate correctly.

4.4. EFFECT OF SERIES CAPACITOR ON CARRIER RELAY:

All important heavily loaded transmission lines are protected with carrier relays either directional comparison or phase comparison type.

The effect of series capacitors on carrier relays will be investigated as follows.

4.4.1. Directional Comparison Carrier Relay:

Directional comparison carrier relay uses directional impedance or mho relays for the starting and blocking purposes, and this relays can be used in the compensated lines.

In case the capacitor is located at the centre of the line and percentage of series compensation is less than 50%, there is no difficulty with the high speed operation of the directional comparison carrier relay.

If the capacitor's location and percentage of compensation are such that for some internal fault, the reactance from the fault point to the relay location is capacitive. the directional element of the impedance relay will not operate correctly.

Even for the mho relay such fault will lie outside the protected zone. Therefore the carrier relay will not operate for such internal faults. However, if the capacitor's sparkgap setting is such that it will break down due to fault current, then the directional carrier relay will operate correctly.

Therefore for the correct operation of directional comparison carrier relay for such systems, it should be assured that the gaps will break-down even for minimum fault current.

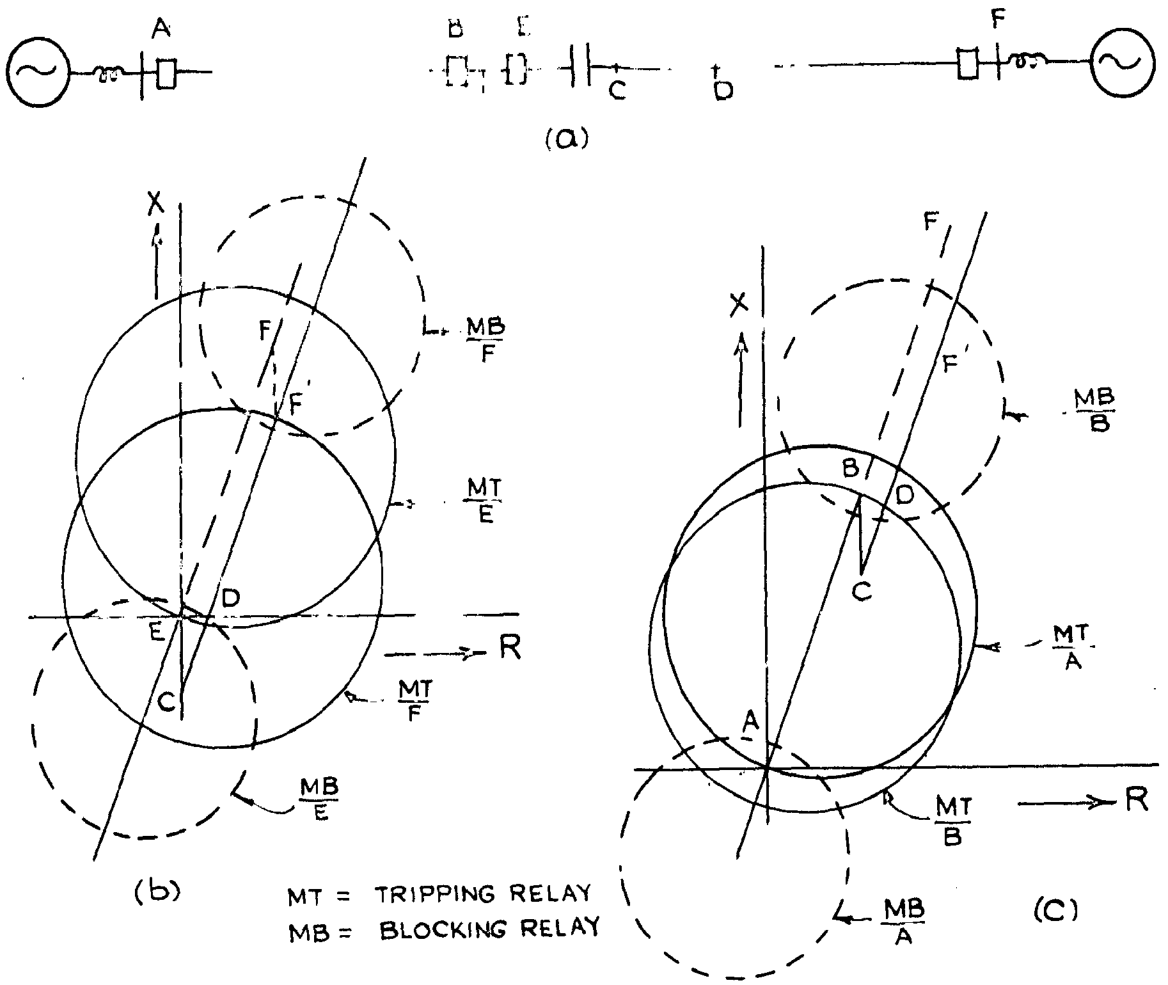
For further clarification the system shown in Fig.(4.4a) may be considered. The directional comparison carrier relay uses mho relays of which MTs are tripping and MBs are blocking relays.

The operation of the carrier relay for the section EF can be explained with the help of Fig.(4.4b).

In Fig.(4.4b), ECDF' is the impedance of the line when the series capacitor is in the circuit and EF is the line impedance when the capacitor is short circuited. Any fault in DF' portion of the line will be cleared by the carrier relay without any time delay, because it falls in tripping zone of the relays at E and F. But for the faults in portion CD of the line, the operation of carrier relay has to be delayed, till the operation of sparkgaps. Without sparkgap operation, the carrier relay will not be able to trip, because the blocking relay MB at E will block the operation of carrier relay.

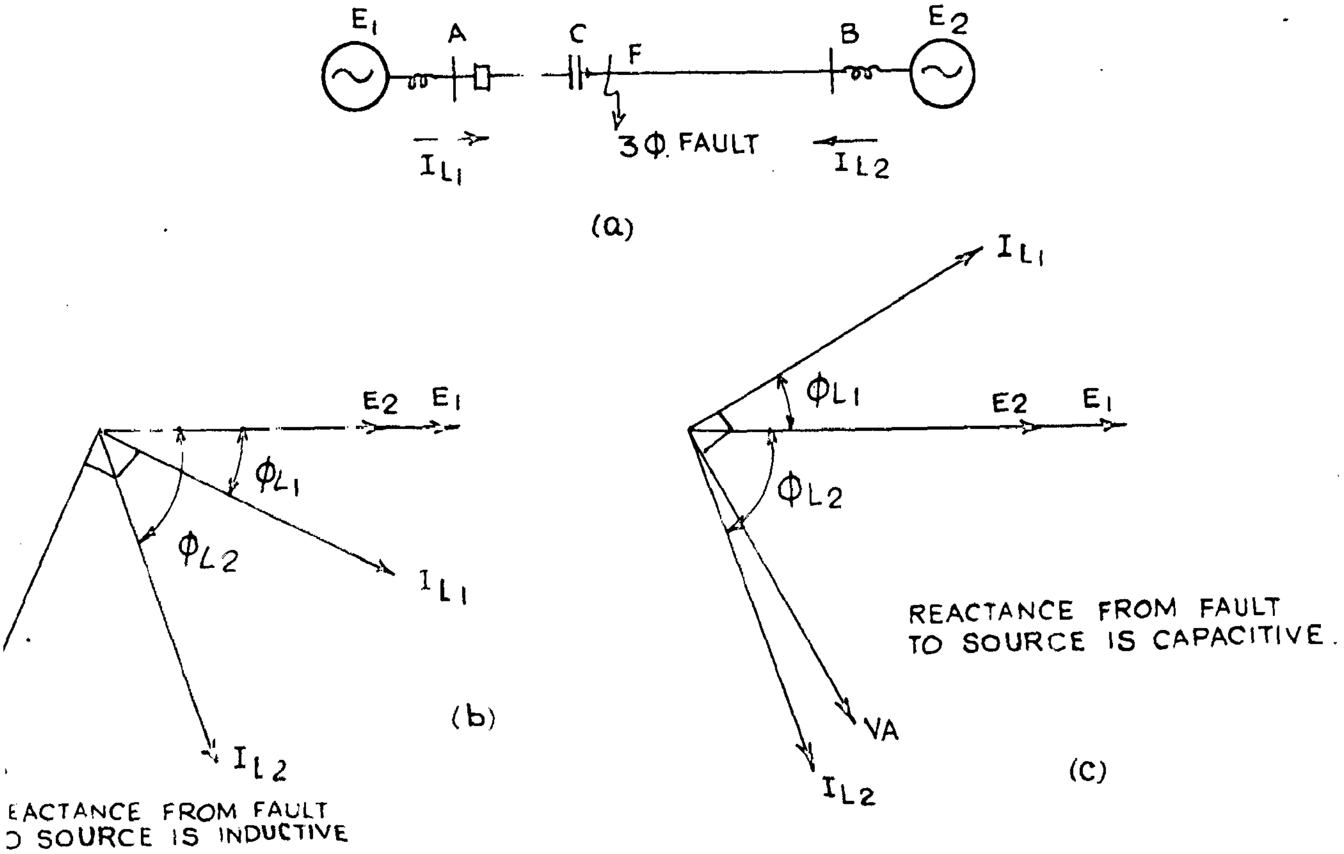
Therefore directional comparison carrier relay has to depend upon the sparkgap operation.

Similarly it can be shown that the carrier relay for AB section of the line, will also be affected by the series capacitor. From Fig.(4.4c) it is clear that the carrier relay will operate correctly



MT = TRIPPING RELAY
MB = BLOCKING RELAY

FIG. 4 4 DIRECTIONAL PHASE COMPARISON CARRIER RELAY IN COMPENSATED LINE.



G. 4.5 VECTOR DIAGRAM FOR PHASE COMPARISON CARRIER RELAY for all internal faults.

But the external fault in portion CD of the line will also enter into the tripping zone and the carrier will operate for such faults. The carrier relay can be prevented from tripping, for the external faults if it can be assumed that the sparkgap will flashover for all such type of faults.

Another factor which affects the correct operation of directional comparison carrier relay, is the circulating current. For remote 3-phase fault or heavy load swings, one sparkgap may operate, which gives rise to circulating current in the system. If the magnitude of this circulating current exceeds the current setting of the residual relay, there is every possibility of false operation of carrier relay. To prevent this undesirable tripping, the setting of the residual relay should be kept at higher value than the maximum circulating current that may appear in the system due to one gap operation.

4.4.2. Phase Comparison Carrier Relay:

Phase comparison carrier relay is nothing but an over-current relay which compares the phase angles of the current at the two ends of the protected line, via a carrier channel. The maximum closing torque for the relay is obtained when the current exceeds the fault magnitude and the phase difference is zero degree, which is the condition obtained for internal faults, neglecting the effect of charging current.

Phase comparison carrier relay scheme can be applied for the protection of the compensated line.

It will always give correct relay operation for the external faults irrespective of the location and percentage of series compensation, because the phase angle of the through fault current will not be affected by the presence of series capacitor in the line.

For internal faults the relay will operate correctly if the reactance from the fault point to sources is inductive.

In Fig.(4.5a), a 3-phase fault has been considered at F near the capacitor. The reactance from the fault point to the sources E_1 and E_2 may be assumed as inductive.

Now due to the presence of series capacitor, the phase angle of I_{L1} will be smaller than the phase angle of I_{L2} which is given by line impedance angle. With the special kind of phase comparison carrier relay, designed to operate even for a phase difference of 90^o, there will be no problem of clearing this type of fault.

But if the reactance from the fault point to one of the source is capacitive, the carrier relay will not operate. As shown in Fig.(4.5c) the phase difference of the fault currents at the two ends will be such that the fault will appear to the relay as an external fault. However in such cases there is every possibility of break-down of spark gap, and this will give a chance to the carrier relay to operate correctly.

CHAPTER 5

PROTECTIVE SCHEMES

5.1. INTRODUCTION:

It has already been discussed that the conventional relays are not so effective in case of series compensated lines. Depending upon the percentage of compensation and the location of series capacitors, relays may fail to operate correctly in a compensated line. Therefore in such a case it is necessary to modify the protective schemes.

Moreover it has been found that the unpredictable nature of the gap operation in the compensated line, creates lot of confusion to correct relaying. Therefore in modifying the protective schemes, care should be taken that the relays can operate correctly irrespective of gap operation.

Here a few protective schemes have been suggested which may be applied for the series compensated line. However, due to shortage of time the experimental verification was not possible.

5.2. POLARISED MHO RELAY SCHEME:

When the location and the percentage of series compensation are such that a portion of the line impedance falls on the fourth quadrant of the R-X diagram, that portion of line will be outside the tripping zone of the conventional mho relay. Therefore, in such cases it is necessary to shift the relay characteristic to the fourth quadrant, so that the whole of the line impedance is covered.

By giving proper polarisation to the conventional mho relay it is possible to shift the relay characteristic to the fourth quadrant, without destroying its directional property. There are three possible practical alternative choices for polarising voltage. For example polarising voltage for the phase relay 'YB' can be any one of the three combinations given below.

(1) Combination of V and V

(2) Combination of V_{YB} and V_{YR}.

(3) Memory circuit associated with V_{YB}.

For the proposed polarised mho relay scheme, polarising voltage of the combination of V_{YB} and V_R has been considered.

In a compensated line when the series-capacitor is short circuited, line impedance changes abruptly. As a result some faults may lie outside the relay characteristic designed to protect the compensated line. This problem has been solved in the proposed scheme by making use of an arrangement to increase the forward reach of the mho relay when the capacitor in the line is short-circuited.

5.2.1. Principle of the Proposed Mho Relay:

In Fig.(5.1b) ACDB' and ACB are respectively the impedances of the line with and without series capacitor. Two mho relay characteristics M_1 and M_2 per phase will be necessary to protect the line completely, as shown in Fig.(5.1b).

The relay characteristics M_1 and M_2 can be obtained with the help of a static phase comparator as follows.

5.2.1(a). Static Phase Comparator:

The input signals to the phase comparator are S_1 and S_2 where,

$$S_1 = -K_1 V_L + I_L Z_{R1} \underline{/\theta_1 - \phi_L} \qquad \ldots \qquad (5.1)$$

= measuring signal.

$$S_2 = K_2 V_L + I_L Z_P \underline{/\theta_P - \phi_L} \qquad \ldots \qquad (5.2)$$

= polarising signal

and which is given by $(K_2' V_{YB} + K_{YB} V_R)$ obtained from combination 1 of 5.2.

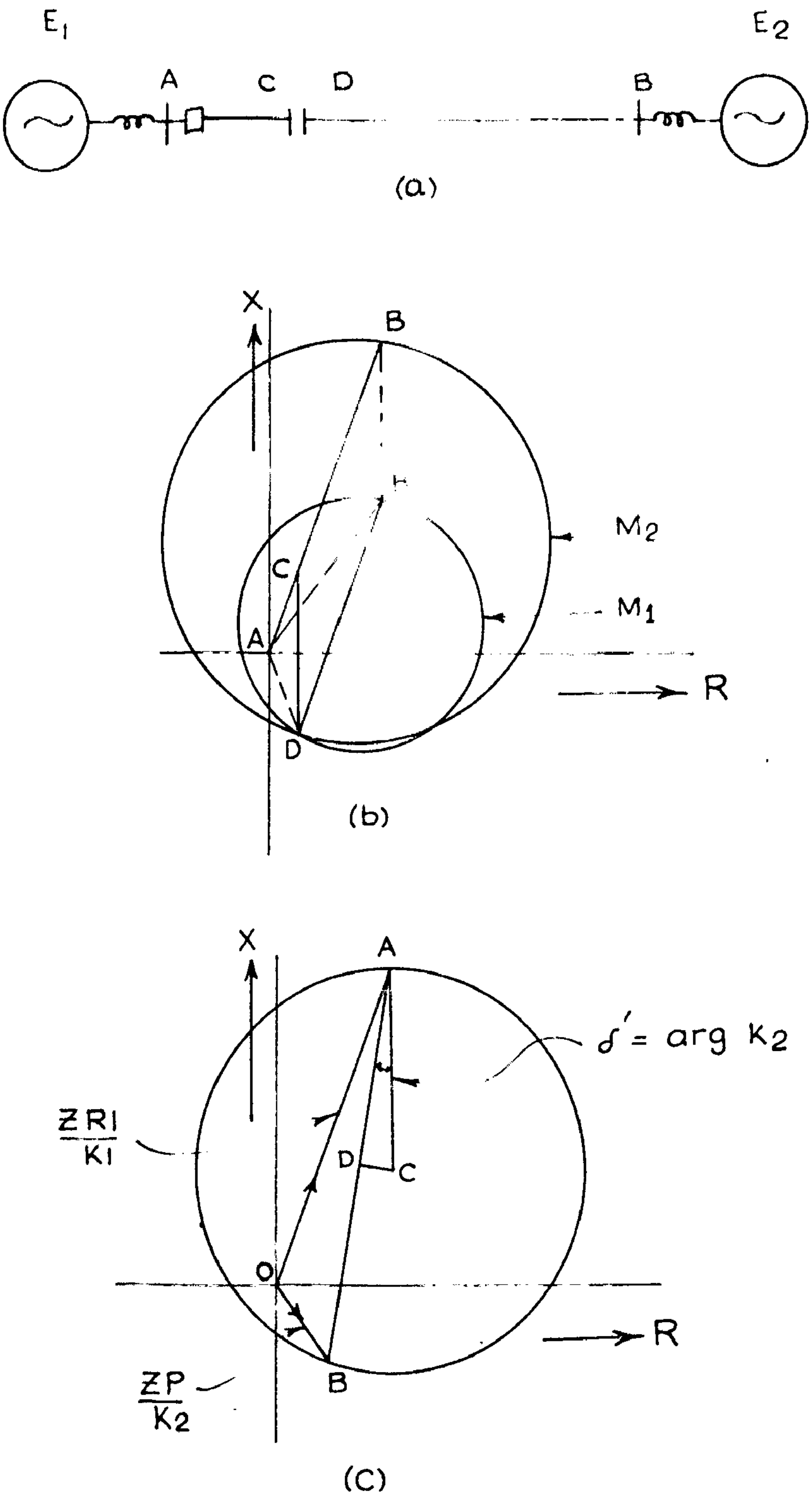


FIG. 5.1. POLARISED MhO-RELAY CHARACTERISTIC

K_1 = Constant and equals to unity

Z_{R1} = Replica impedance of the line.

$K_2 = K_2' + 1/\sqrt{3}\ |K_{YB}|$

$K_2' = 1\ \underline{/0^\circ}$

$K_{YB} = 1\ \underline{/\theta_{YB}}$,

and θ_{YB} = Phase shift given to V_R w.r.t. V_{YB}

$Z_P = 1/\sqrt{3}\ |K_{YB}|\ Z_s$, and Z_s = Source impedance.

The comparator is designed to operate for the coincidence angle $-90^\circ \leqslant \phi \leqslant 90^\circ$.

The relay characteristic obtained for this phase comparator can be explained with the help of Fig.(5.1c). The forward reach of the relay is given by Z_{R1}/K_1 and backward reach by Z_P/K_2.

Any value of replica impedance can be chosen to give the relay the required forward reach. But the backward reach depends upon the source impedance of the system.

5.2.1(b). Changing of Replica Impedance:

In Fig.(5.1b) it is shown that two relay characteristics will be necessary to protect the line with and without the series capacitor. But instead of using two relays, only one relay will be used in the proposed scheme. By changing the value of the replica impedance of the phase comparator, the mho relay characteristics M_1 and M_2 can be obtained from a single phase comparator. The forward reach for the relay M_1 for compensated line is given by $Z_{R1} = R_L + jX_L - jX_C$, the value of K_1 being unity.

An arrangement has been made to short circuit the capacitive reactance of the replica impedance automatically, when the series capacitor in the line is short-circuited. The new replica impedance $Z_{R1} = R_L + jX_L$ will give the relay, sufficient forward reach to cover the whole length of the line without any compensation.

5.2.1.(c). Automatic Switching of Replica Impedance:

To short circuit the capacitive reactance part of the replica impedance during the period, when series capacitor on the line is short circuited, another phase comparator circuit is used. There will be an appreciable change of phase angle of the fault current when the series capacitor in the line is short-circuited. This change of phase angle is utilised to operate the phase comparator which in turn short-circuits the capacitive reactance part of the replica impedance.

52.2. Circuit for the Proposed Mho Relay Scheme:

The circuit for the proposed mho relay scheme is given in Fig.(5.2). The whole scheme consists of three main parts.

Part (1): The circuit to obtain the signals S_1 and S_2.

Part (2): Switching arrangement for the capacitive reactance part of the replica impedance.

Part (3): Static phase comparator circuit to obtain the mho relay characteristics.

Part (1): This circuit is used to obtain the signals S_1 and S_2.

The measuring voltage S_1 is obtained by adding the voltage due to fault current across the replica impedance, with line voltage V_{YB} in a summation transformer.

Polarising voltage $S_2 = -K_2' V_{YB} + K_{YB} V_R$

where, $K_2' = 1 \underline{\angle 0^\circ}$

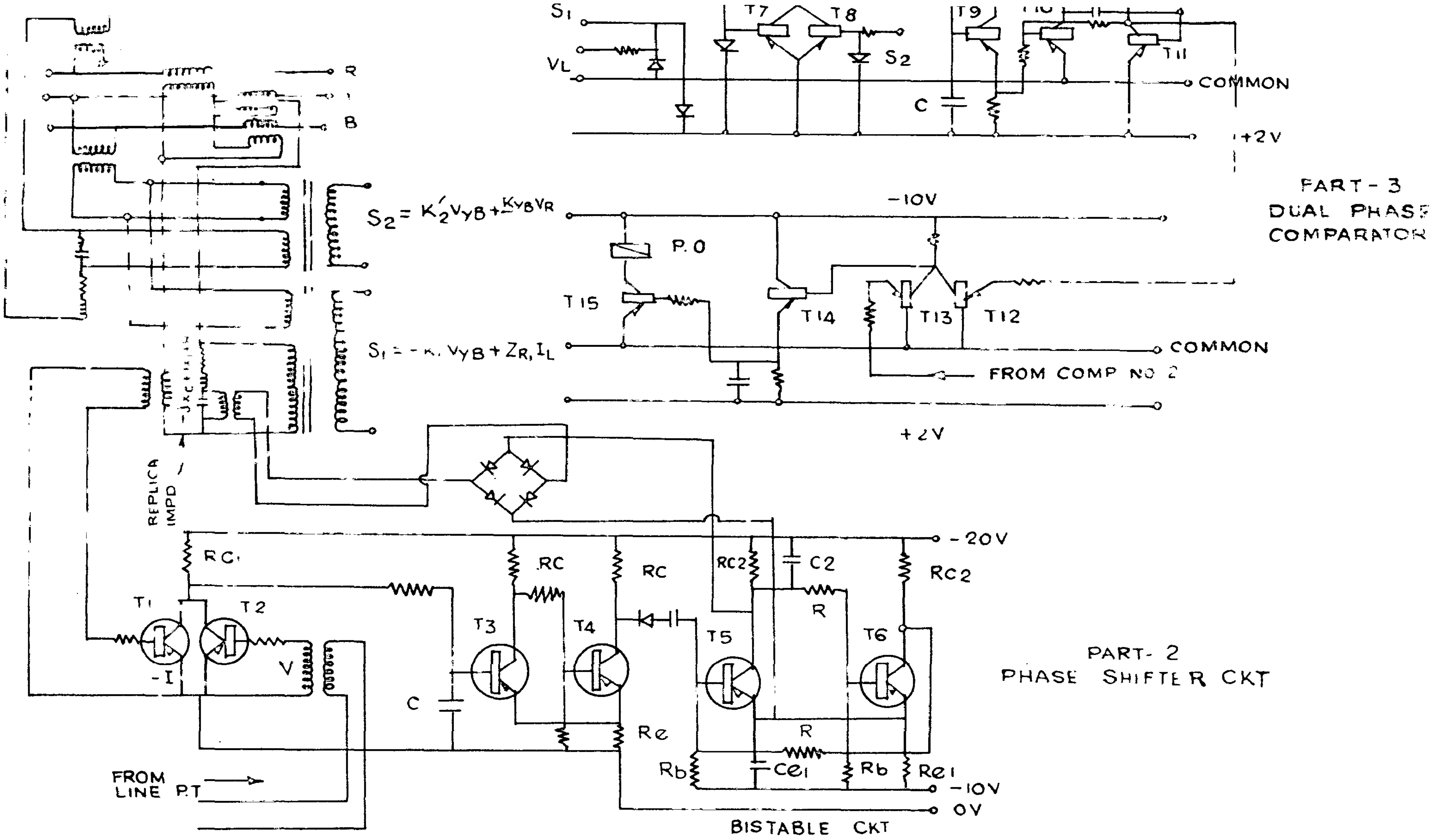


FIG 5 2 CIRCUIT DIAGRAM FOR POLARISED MHO RELALY SCHEME.

$K_{YB} = 1/\underline{\theta_{YB}}$ i.e.

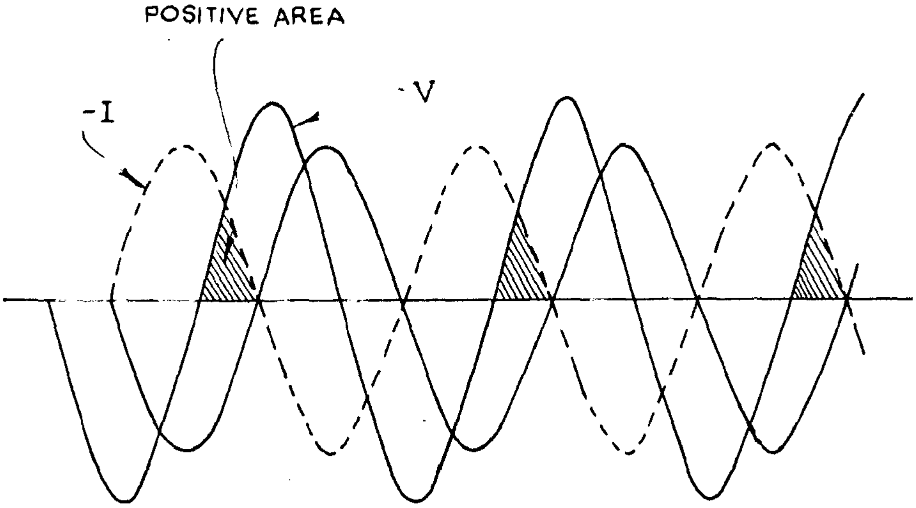
the voltage V_R is given phase shift of $\underline{/\theta_{YB}}$, with respect to V_{YB}. The signal S_2 is obtained by adding the voltages in a summation transformer.

Part (2): This circuit detects whether the series capacitor is present in the line or not and accordingly it short-circuits the capacitive reactance of the replica impedance. A static phase comparator is used for this purpose, and the line voltage and line current (i.e. V and -I) are the inputs given. Refering to the Fig.(5.3b) it is seen that when the series capacitor is short-circuited, the simultaneous positive area between V and -I increases. If the fault current I is sufficient and the time of coincidence exceeds the preset value, the level detector will operate. The level detector in turn triggers the bistable circuit and which will switch on the transistor T_5. When T_5 is switched on, the current will flow through the secondary of the matching transformer connected across the capacitive reactance of the replica impedance, through a diode bridge. Due to the flow of current through the secondary of the matching transformer, capacitive reactance will be short circuited, and the value of replica impedance will be the actual impedance of the line. Therefore, with the help of this circuit it is possible to change automatically, the value of replica impedance, and thereby increasing the reach of the mho relay.

Part (3): Dual phase comparator circuit is used to obtain the mho relay characteristics. The circuit is as shown in Fig.(5.2).

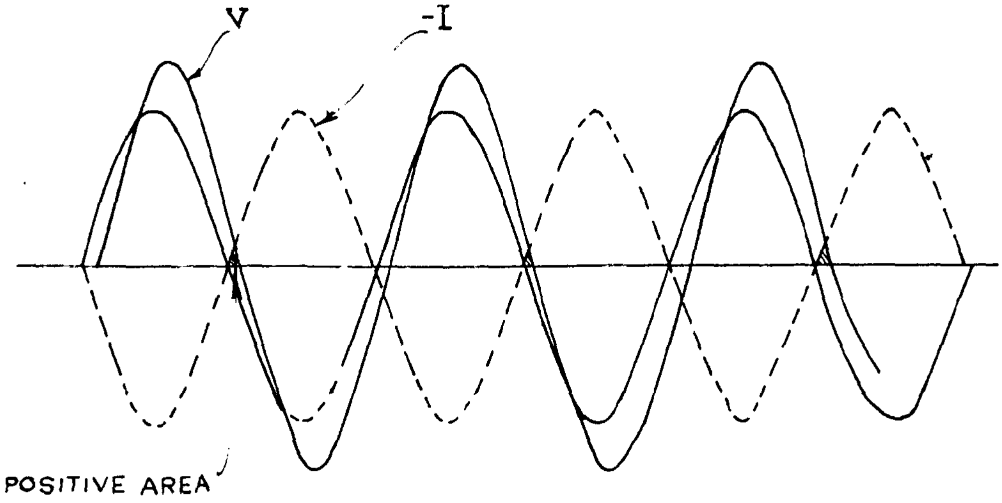
5.2.3. Application of the Scheme:

A practical example of the use of the relay scheme in a compensated line is given in A.3.1. of Appendix 3.



(b)

WITHOUT SERIES CAPACITOR IN THE CIRCUIT



(a)

WITH SERIES CAPACITOR IN THE CIRCUIT

FIG. 5.3 INPUT TO THE PHASE COMPARATOR.

5.2.4. Discussions:

Advantages:

(1) This scheme is applicable to the series compensated line and can be used when the impedance of the line falls in the fourth quadrant of the R-X diagram.

(2) The correct operation of the relay does not have to depend upon the operation of the sparkgap. Therefore, it has less possibility of faulty operation.

(3) No intentional time delay is necessary.

Disadvantages:

The main drawback of the scheme is that it can be applied only to those systems which have sufficient source impedance. The backward reach of the relay depends mainly upon the source impedance. Hence it can not be used in all cases. However for all practical purposes this scheme seems to be quite applicable.

5.3. PROTECTIVE SCHEME WITH QUADRILATERAL RELAY CHARACTERISTIC:

The quadrilateral relay characteristic as shown in Fig.(5.4) is the ideal relay characteristic to be used for the protection of series compensated line. With this shape of relay characteristic, the protection of tie line can be given irrespective of the percentage of compensation and the location of the series capacitor.

Another advantage with this scheme is that it is not affected by the sparkgap operation.

5.3.1. Principle of Relay Operation:

The proposed relay scheme uses two static phase comparators, to obtain the quadrilateral relay characteristic.

Phase comparator No.1 having input signals S_1 and S_2 will

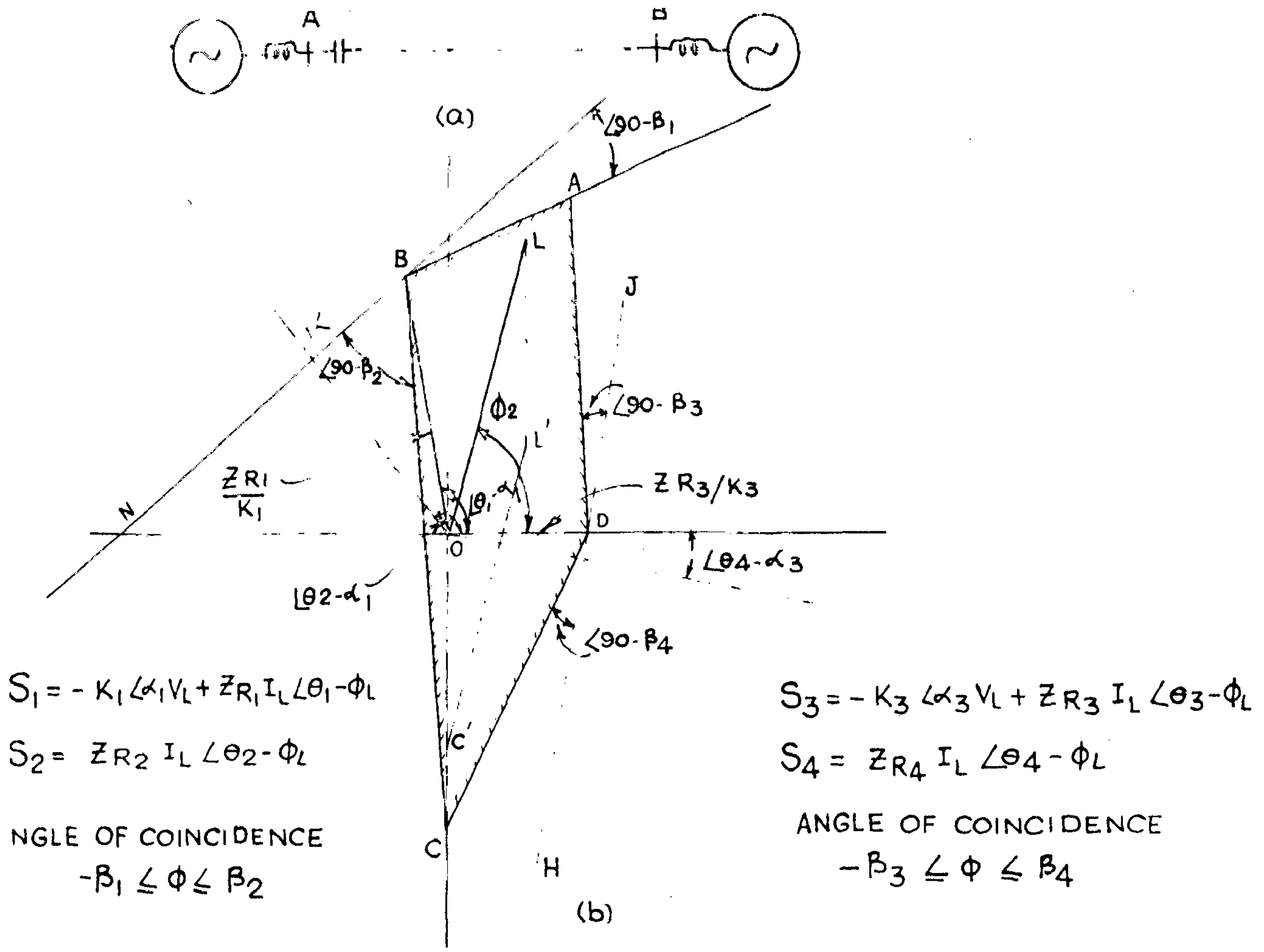
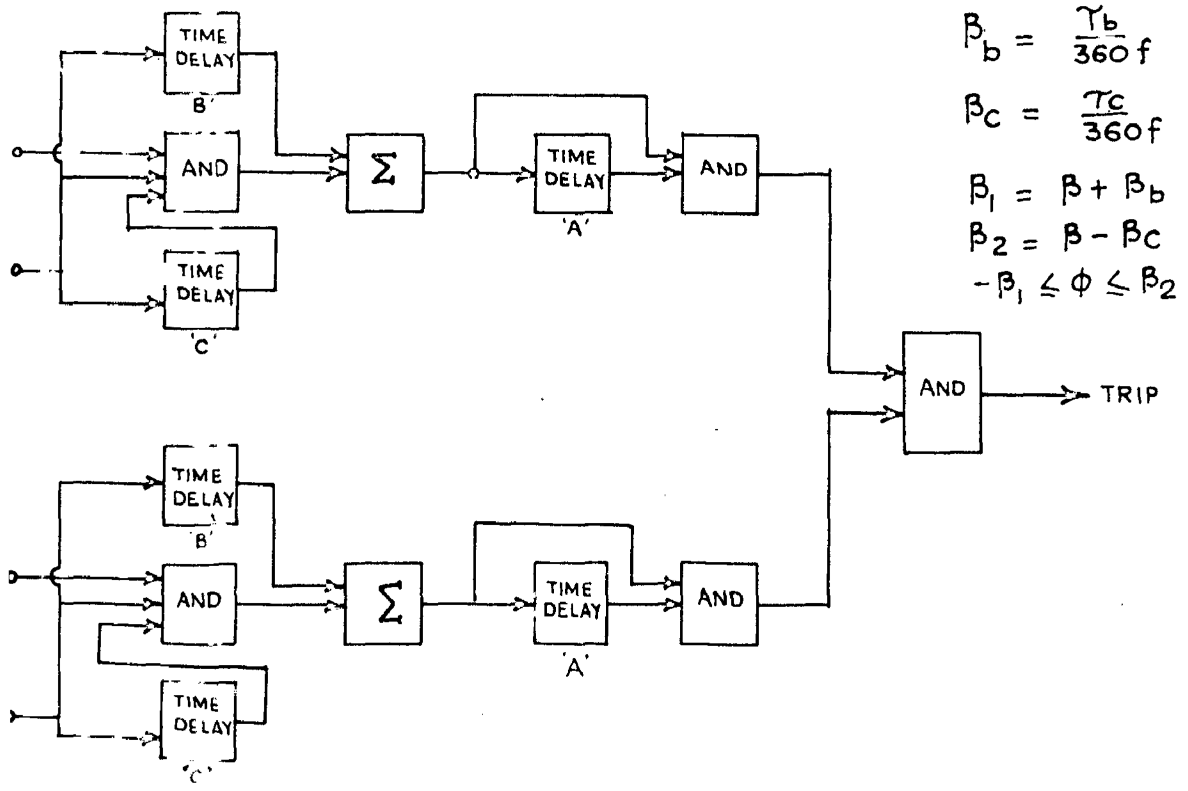


FIG. 5.4 QUADRILATERAL RELAY CHARACTERISTIC BY USING TWO STATIC PHASE COMPARATORS



5.5 BLOCK DIAGRAM FOR UN-SYMMETRICAL STATIC PHASE COMPARATOR.

give tripping area ABC shown shaded in the Fig.(5.4).

The other phase comparator No.2, having inputs S_3, S_4 will give the tripping area ADC shown shaded in the same figure. The net tripping area ABCD shown shaded in the Fig.(5.4), is obtained by combining the output of the two comparators. The relay characteristic is made sufficiently big to accomodate the whole of the line impedance with and without the series capacitor. Therefore the gap operation will not have any effect on the operation of the relay. The details of the static phase comparator are given below.

For the phase comparator No.1. the input siggals are-

$$S_1 = -K_1 \underline{\angle \alpha_1}\ V_L + Z_{R1}\ I_L\ \underline{/\theta_1 - \phi_L} \quad \ldots \quad (5.3)$$

$$S_2 = Z_{R2}\ I_L\ \underline{/\theta_2 - \phi_L} \quad \ldots \quad (5.4)$$

where,

$V_L\ \underline{\angle 0^\circ}$ = Fault voltage at the relay terminal.

$I_L\ \underline{/\phi_L}$ = Fault current at the relay terminal.

$K_1\ \underline{/\alpha_1}$ = Transformation ratio, complex quantity,

$Z_{R1}\ \underline{/\theta_1}$ and $Z_{R2}\ \underline{/\theta_2}$ = Replica impedances.

To obtain the desired relay characteristic, S_1 and S_2 must satisfy conditions given below.

$$K_1 Z_L \operatorname{Cos}(\theta_2 - \alpha_1 - \phi_L) + Z_{R1} \operatorname{Cos}(\theta_2 - \theta_1) \geqslant -\operatorname{Cot}\beta_1 \left\{ K_1 Z_L \operatorname{Sin}.(\alpha_1 - \theta_2 + \phi_L) + Z_{R1} \operatorname{Sin}(\theta_1 - \theta_2) \right\} \quad \ldots \quad \ldots \quad (5.5)$$

$$K_1 Z_L \operatorname{Cos}(\theta_2 - \alpha_1 - \phi_E) + Z_{R1} \operatorname{Cos}(\theta_2 - \theta_1) \geqslant \operatorname{Cot}\beta_2 \left\{ K_1 Z_L \operatorname{Sin}.(\alpha_1 - \theta_2 + \phi_L) + Z_{R1} \operatorname{Sin}(\theta_1 - \theta_2) \right\} \quad \ldots \quad \ldots \quad (5.6)$$

Where $\angle\beta_1$ and $\angle\beta_2$ are the limits of the coincidence angle of the comparators i.e. coincidence angle ϕ of the comparator is given by $-\beta_1 \leqslant \phi \leqslant \beta_2$

Having satisfied this condition the comparator will give the relay characteristic ABC as shown shaded in Fig.(5.4). Vector $OB = Z_{R1}/K_1 \underline{/\theta_1} - \alpha_1$ and $\underline{\angle ABM} = \underline{\angle(90} - \beta_1)$ and $\underline{\angle NBC} = \underline{/90} - \beta_2$ and $\underline{\angle DOK} = \underline{/\theta_2} - \alpha_1$.

Similarly the input to the second phase comparator are-

$$S_3 = -K_3 \angle\alpha_3 V_L + Z_{R3} I_L \underline{/\theta_3} - \phi_L \quad \ldots \quad \ldots \quad (5.7)$$

$$S_4 = Z_{R4} I_L \underline{/\theta_4} - \phi_L \quad \ldots \quad \ldots \quad (5.8)$$

where,

$K_3 \underline{\angle\alpha_3}$ = Voltage transformation ratio,

$Z_{R3} \underline{/\theta_3}$ and $Z_{R4} \underline{/\theta_4}$ = replica impedances.

The following equations have to be satisfied to get the required relay characteristic ADC as shown shaded in Fig.(5.4).

$$K_3 Z_L \mathrm{Cos}(\theta_4 - \alpha_3 - \phi_L) + Z_{R3} \mathrm{Cos}(\theta_4 - \theta_3) \geqslant -\mathrm{Cot}\,\beta_3 \left\{ K_3 Z_L . \mathrm{Sin}\,.\,(\alpha_3 - \theta_4 + \phi_L) + Z_{R3} \mathrm{Sin}\,(\theta_3 - \theta_4) \right\} \quad \ldots \quad \ldots \quad (5.9)$$

$$K_3 Z_L \mathrm{Cos}\,(\theta_4 - \alpha_3 - \phi_L) + Z_{R3} \mathrm{Cos}\,(\theta_4 - \theta_3) \geqslant \mathrm{Cot}\,\beta_4 \left\{ K_3 Z_L \mathrm{Sin}\,.\,(\alpha_3 - \theta_4 + \phi_L) + Z_{R3} \mathrm{Sin}\,(\theta_3 - \theta_4) \right\} \quad \ldots \quad (5.10)$$

where β_3 and β_4 are the limits of the coincidence angle i.e.

$$-\beta_3 \leqslant \phi \leqslant \beta_4$$

In Fig.(5.4) vector $OD = ZR_3/K_3 \underline{/\theta_3} - \alpha_3$

$\angle ADJ = \angle 90 - \beta_3$, $\angle HDC = \angle 90 - \beta_4$

The outputs from the phase comparators are fed to an 'AND' gate which gives the final ∅ tripping pulse to trip coil.

5.3.2. Circuit Diagram:

The static phase comparators are of special type. Unlike the conventional phase comparator, its angle of coincidence is asymmetrical. For example, limits of angle of coincidence for comparator No.1 is given by $-\beta_1 \leqslant \emptyset \leqslant \beta_2$ where $\beta_1 \neq \beta_2$

The block diagram of the whole scheme is given in Fig.(5.6) The required circuit consists of 'AND' gates, summers and time delay circuits required to obtain the asymmetrical coincidence angles.

Considering comparator no.1, the angle of coincidence $\emptyset$ which lies in between $-\beta_1 \leqslant \emptyset \leqslant \beta_2$ can be obtained as follows.

$\beta_1 = \beta + \beta_b$ where β = symmetrical coincidence angle of the phase comparator.

and $\beta_b = \frac{\tau_b}{360f}$

By giving time delay τ_b, angle β_b can be obtained.

Similarly $\beta_2 = \beta - \beta_c$

$\beta_c = \frac{\tau_c}{360f}$

Here time delay τ_c is given to obtain β_c.

The same procedure is followed for the phase comparator No.2 to obtain the asymmetrical coincidence angles.

5.3.3. Application of the Scheme:

A practical scheme has been discussed in A.3.2 of Appendix 3.

5.4. PHASE COMPARISON CARRIER RELAY SCHEME:

Phase comparison carrier relay is the most suitable protective scheme to be used for long heavily loaded transmission lines.

It can be used with certain modifications to protect the series compensated transmission lines. However, before using it to protect the series compensated line the following points have to be given proper consideration. For the correct operation of phase comparison carrier relay, it is necessary that the impedance of the line from the point of fault upto the source should be always inductive. Secondly if the impedance from the fault upto the souce is capacitive, the sparkgaps should always break-down under any type of fault condition.

There are mainly two types of phase comparison carrier relays that can be used for the series compensated transmission line. One is standard form of overcurrent phase comparison carrier relay which is most commonly used, and the other type uses mho relay to control the phase comparison carrier relay.

The difficulty with the former type of phase comparison carrier relay is that for the correct operation of the relay, the ratio of minimum fault current to the maximum load current, should be always greater than unity, for any type of fault condition. But in a series compensated line minimum 3-phase fault current may be less than maximum load current. Therefore the use of this type of relay is not favoured in a compensated line.

By using the mho relay to control the phase comparison carrier relay, its sensitivity can be increased considerably. It can be used even in such systems where 3-phase fault current may be less than the maximum load current.

5.4.1. Mho-supervised Phase Comparison Carrier Relay:

With the help of mho supervised phase comparison carrier relay scheme, the selectivity, speed and reliability as required for the modern power systems, can be achieved.

This type of relay consists of the following components, one standard phase comparison carrier relay, three units of mho distance relays (one relay per pair of phases), and one carrier ground relay, Each unit contains three mho relays per phase, while ground carrier relay has one directional and two instantaneous over current relays. The phase comparison carrier relay provides 3-phase, phase to phase and line-to-ground fault protection. Another purpose of mho relay is to unbalance negative sequence network to provide a positive sequence output for a 3-phase fault.

5.4.2. Operation Principle:

For the given system the mho relay characteristics per phase for each terminal is shown in Fig.(5.6a,b). The centres of the mho relay circles at terminal A, lie on line FAB', whereas for the relays at terminal B, the centres will lie on CBE when the series capacitor is in the line, and lie on FAB' when the capacitor is shunted off by the gaps.

The working, setting and co-ordination of these relays can be explained as follows.

MT units at the each terminals are the trip permissive relays. It is set in such a fashion, that it can detect any phase

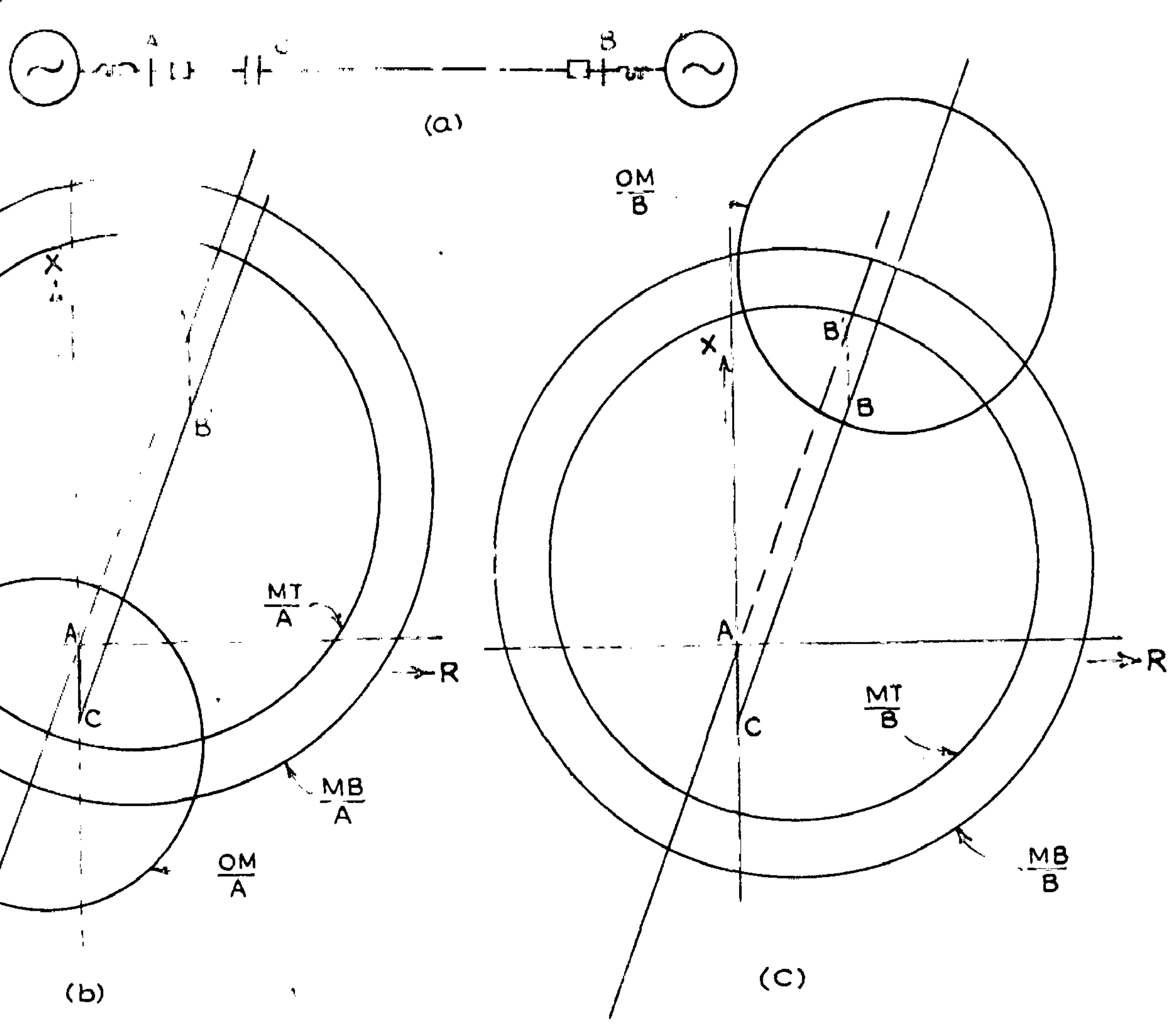
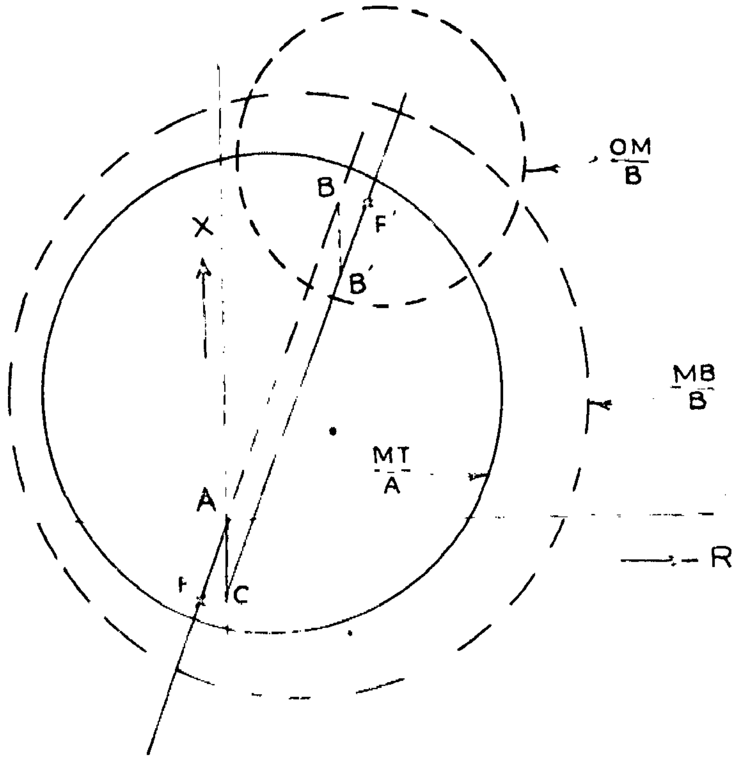


FIG. 5.6 Mho-RELAYS FOR CONTROLLING PHASE COMPARISON CARRIER.



5.7 CO-ORDINATION OF Mho-RELAYS AT THE TWO ENDS OF PROTECTED LINE.

fault&set up the trip circuit. The final tripping operation is done by phase comparison carrier relay. The relay characteristic is given sufficient over reach and offset so that it can detect any internal phase fault for the line with or without the series capacitors.

Mho relays MB and OM are used as starter for phase comparison carrier relays for both internal and external faults. Another use of these relays are to shift the negative sequence network for 3-phase fault in the systems. MB and OM relays are co-ordinated with MT relay at the opposite terminals in such a fasion that it can detect and start carrier blocking for those external faults which are within the reach of tripping relays at the opposite terminal.

In Fig.(5.7) the co-ordination of tripping relay at A with the blocking relays at B for faults external to A such as at F is shown. OM unit is required to ensure the fast starting of phase comparison carrier relay for faults external to A such as at F'. This relay is required, because it may happen that MT and MB unit at A may pick up for external faults at F' before MB unit at B have a chance to pick up and start phase comparison blocking. Once MT and MB units at any terminal pick up and the fault current exceeds the phase comparison carrier pick up, that terminal will trip unless it is blocked by carrier relay from the opposite terminal.

Similarly the tripping relay at B is co-ordinated with the blocking relays MB and OM at A.

The ground fault relay is used in the same way as the mho units. The directional overcurrent units of this relay are used as permissive units. They detect internal ground faults and establish the trip circuit. The overcurrent relay is used to start phase comparison carrier relay.

In case where there is possibility of false operation of directional unit, only the overcurrent relay is used.

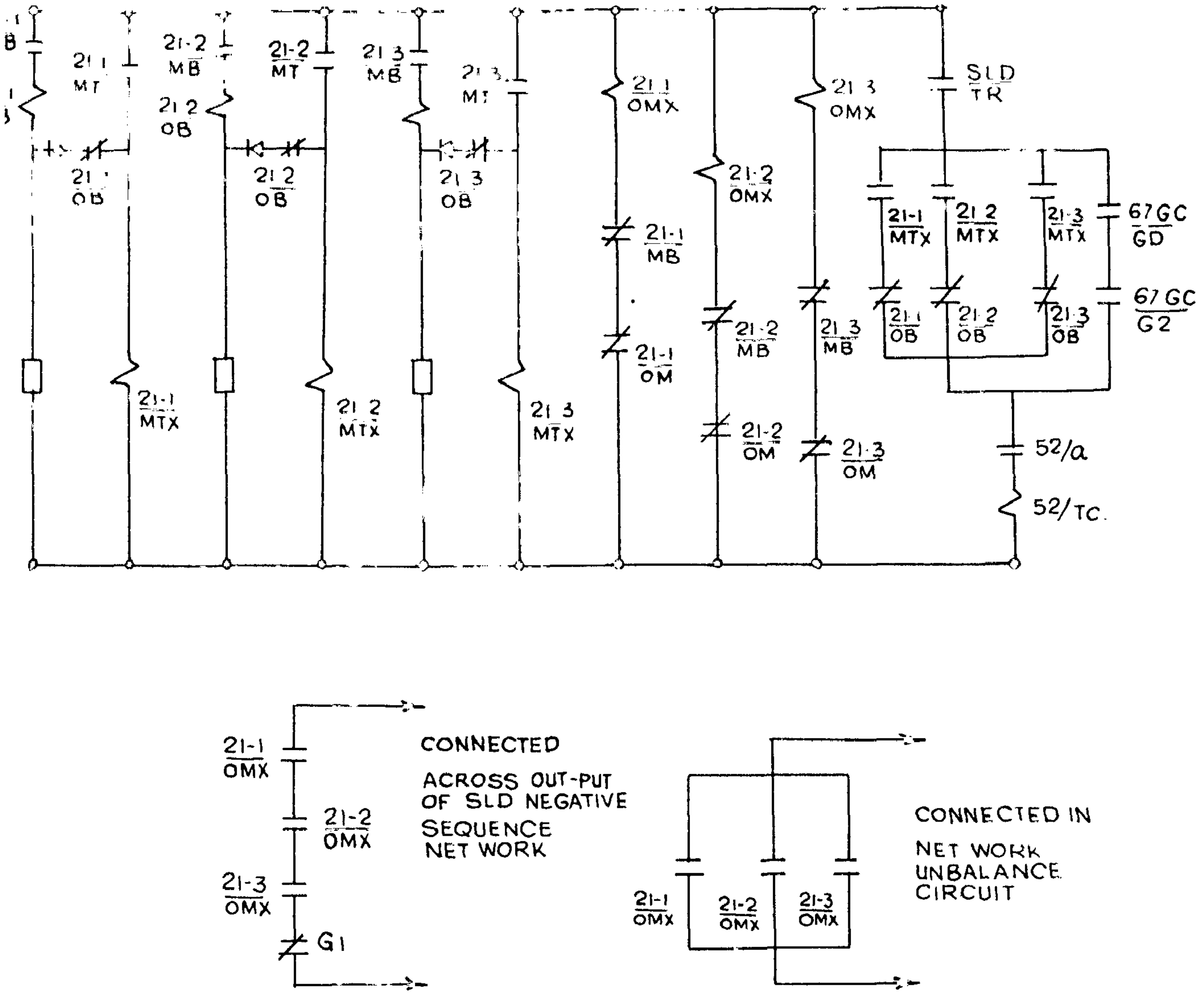
5.4.3. Control Diagram:

The controlling of the phase comparison carrier relay, by mho relays is described briefly in the following paragraphs.

From the Fig.(5.8) it is seen that under healthy condition normally closed contacts MB and OM unit will energise three auxillary OMX relays. The contacts from the auxilliary relays and a normally closed contact G_1 are connected in series across the output of phase comparison carrier relay SLD network unit. As all these contacts will remain closed under healthy condition, the output of the network will be shorted and SLD (phase comparison) relay, will be inoperative.

Three other normally open OMX contacts in parallel are connected across the net-work unbalancing circuit. When one or more of these contacts is closed, the network will provide its normal negative-sequence output. In case of 3-phase fault, all the contacts will remain open, as a result the network will be shifted to provide a positive sequence component for 3-phase fault protection.

In case of phase fault in the system one or more unit of OM or MB will pick up, and as a result one or more auxillary relay OMX will reset and the network will produce an output. If the fault current is sufficient, the phase comparison carrier relay will compare the phase angles of the currents at the two ends. In



CONNECTED ACROSS OUT-PUT OF SLD NEGATIVE SEQUENCE NET WORK

CONNECTED IN NET WORK UNBALANCE CIRCUIT

21/MT = TRIP PERMISSIVE UNIT

21/MTX = AUXILIARY TO MT

52/TC = CB TRIP COIL

52/a = CB SWITCH

21/MB & 21/OM = STARTING UNIT FOR PHASE COMPARISON

21/OMX = AUXILIARY TO PHASE COMPARISON START UNIT

21/OB = OUT OF STEP BLOCKING AUXILIARY UNIT

67GC/GD = DIRECTIONAL UNIT OF DIRECTIONAL OVER CURRENT GROUND RELAY

67 GC/G2 = INSTANTANEOUS O C OF DIRECTIONAL GROUND

SLD/TR - PHASE COMPARISON TRIP RELAY

FIG. 5.8 SIMPLIFIED CONTROL DIAGRAM

case of internal faults MT relay will pick up and establish the trip circuit through contact MTX, and the phase comparison carrier relay will trip the breaker through the contact TR.

In case of ground fault, the over-current unit G_1 will pick up and permit a comparison of the line current by SLD phase comparison relay. If the fault directional unit GD and G_2 will pick up and establish the trip circuit the phase comparison relay will trip the breaker through the contact TR.

CHAPTER 6

CONCLUSION

The modified mho relay scheme as has been suggested in Chapter 5 of this dissertation may be used for most of the series compensated lines. This relay does not have to depend upon the flashover of sparkgaps for its correct operation and no time delay is required. Therefore it is suitable for high speed operation. However, before using this relay scheme, it must be ascertained that there is sufficient source impedance to shift the relay characteristic to the fourth quadrant, so that the whole of the compensated line is completely protected.

In the proposed quadrilateral relay characteristic scheme, there is no restriction of size and location of series capacitor. As shown in Appendix 3, the line can be protected with the help of this scheme even when the series capacitor is located at the sending end and the magnitude of line compensation is upto 75%. Moreover due to its restricted tripping area, this relay will maintain excellent selectivity and hence will be uneffected by heavy load swings. In the proposed relay scheme, given in Chapter 5, the required quadrilateral relay characteristic is obtained with the help of two unsymmetrical static phase comparators However the same relay characteristic may be obtained with the help of a multi-input static phase comparator, which needs further investigation.

The mho supervised phase comparison carrier scheme is applicable to series compensated lines, provided there do not exist any capacitive fault point from either of the sources. Mho relays used for controlling the phase comparison carrier scheme, have sufficiently large relay characteristics, to allow heavy load swings to enter into the tripping area. But there will be no unwanted relay operation, because of the fact that the ultimate tripping is done by the phase comparison carrier relays. However for an extra high voltage long line, due to charging current, there may exist an appreciable phase difference between the currents at the two ends even if there is no internal fault. In such a case phase comparison carrier relay may give false operation due to heavy load swings. Instead of a mho relay if a quadrilateral relay characteristic, is used for controlling the carrier operation, such in correct operation due to power swings may be avoided. The applicability of quadrilateral relay characteristic as a controlling unit, for phase comparison carrier relay requires further investigation.

APPENDICES

APPENDIX I

A-1.1. Line Parameters:

400KV Double Circuit Bundled Conductor Line

480 miles in length.

Conductor A.C.S.R. size 1,033,50 circular mills.

Number of bundle conductor per phase =2

Conductor diameter =1.246"

Sub-Conductor spacing = 18"

Distance of Separation between the phases .. = 32"

X_L, Line Inductive reactance at 50c/s= 0.5ohms/phase/mile.

r_L, Line resistance at 50 c/s = .05ohms/phase/mile.

X'_C, Line capacitive reactance at 50c/s=0.177Mohms/phase/mile

Z'_0, Zero sequence impedance = 0.198+j1.028 ohms/phase/mile

Surge Impedance .. = 301 ohms.

Surge Impedance loading of the line $= \frac{2 \times 1000}{301} (KV)^2$

$= 1060$ MW.

A-1.2. Cost Datas:

Obtained from Central Water Power Commission, New Delhi.

(1) Cost of Double Circuit Transmission line per mile=₨.8,91,000/-

(2) Transformers .. 400/220KV

(a) 100 MVA	..	₨.30,00,000/-
(b) 200 MVA	..	₨.46,32,920/-
(c) 350 MVA	..	₨.50,00,000/-
(d) 500 MVA	..	₨.56,50,000/-

Cost of errection is 20% of the capital cost.

(3) Cost of Intermediate sub-station per Breaker position ₨.33,60,000/-

(4) Cost of Series and shunt capacitors ₨.100/KVAr

(5) Cost of Electrical Energy loss =₨.1200/KW +5.5P/KWh at 40% Loss factor.

(6) Annual charge 10%, Annual load factor is assumed 60%.

A.1.3. Transient Stability limit for different percentage of Compensation.[15]

TABLE NO.A-1.1.

For Method 1 *Reactive Power at the receiving end has been calculated.

No.of switching substations	Percentage of series compensation	Transient stability limit in p.u.of S.I.L.	Actual value of transient stability limit in (MWs)	*Reactive Power at the receiving end (MVAr)
1	2	3	4	5
1	0	.460	488	
	10	.538	570	
	20	.600	635	
	40	.738	784	
	50	.800	849	
	60	.870	921	
	70	.92	975	250
	80	1.0	1060	300
2	0	.62	668	
	10	.68	720	
	20	.75	795	
	40	.90	955	
	50	.96	1038	
	60	1.02	1080	60
	70	1.12	1188	420
	80	1.2	1272	500

Table No.A-1.1. contd.

1	2	3	4	5
3	0	.72	765	
	10	.80	848	
	20	.86	911	
	40	1.02	1080	20
	50	1.10	1165	65
	60	1.18	1250	190
	70	1.29	1368	575
	80	1.40	1482	680
4	0	.80	848	
	10	.88	932	
	20	.95	1010	
	40	1.12	1188	100
	50	1.21	1281	160
	60	1.32	1400	300
	70	1.43	1515	700
	80	1.56	1650	850
5	0	.82	878	
	10	.90	955	
	20	1.00	1060	60
	40	1.16	1230	140
	50	1.26	1336	200
	60	1.37	1451	350
	70	1.50	1590	750
	80	1.64	1740	950

TABLE NO.A-1.2

Method 2

No.of intermediate substations	Percentage of series compensation	Transient stability limit in p.u.of S.I.L.	Actual value of transient stability limit(in MW)	Reactive power at the receiving end (in MVAr)
1	2	3	4	5
0	20	.38	403	
	40	.55	584	
	50	.68	721	
	60	.82	870	
	70	1.02	1080	370
1	20	.64	680	
	40	.85	900	
	50	1.00	1060	
	60	1.20	1270	200
	70	1.52	1610	850
2	20	.81	850	
	40	1.02	1080	20
	50	1.18	1250	130
	60	1.40	1481	380
	70	1.74	1845	1100
3	20	.90	955	
	40	1.12	1188	100
	50	1.30	1380	240
	60	1.54	1632	620
	70	1.85	1960	1200

Table No.A-1.2 contd.

1	2	3	4	5
	20	.94	995	
	40	1.18	1250	165
4	50	1.37	1450	310
	60	1.60	1700	700
	70	1.92	2040	1350
	20	1.00	1060	60
	40	1.24	1312	218
5	50	1.40	1485	350
	60	1.64	1740	730
	70	1.94	2058	1350

TABLE No.A-1.3

Method 3 — 3 Intermediate sub-station is assumed.

Initial series compensation in percentage	Percentage of excess series compensation	Transient stability limit in p.u. of S.I.L.	Actual value of transient stability limit in(MW)	Reactive power at the receiving end in (MVAr)
1	2	3	4	5
	0	.82	870	
	20	.86	911	
12.5%	40	.90	950	
	60	.92	975	
	80	1.00	1060	
	100	1.12	1188	125

Table No.A-1.3 contd.

1	2	3	4	5
25%	0	.9	955	
	20	.93	985	
	40	.98	1040	
	60	1.02	1080	20
	80	1.10	1165	120
	100	1.28	1358	380
50%	0	1.12	1188	82
	20	1.16	1230	120
	40	1.23	1310	180
	60	1.33	1410	270
	80	1.48	1570	440
	100	1.72	1821	1000
75%	0	1.33	1410	400
	20	1.46	1548	510
	40	1.60	1697	650
	60	1.80	1910	820
	80	2.06	2181	1120
	100	2.45	2600	1850

TABLE NO.A-1.4

Method 4

30% Initial compensation in the Intermediate busbars, is assumed

No.of Intermediate sub-station	Percentage of series compensation	Transient stability limit in p.u. of S.I.L.	Actual value of transient stability limit in (MW)	Reactive power at the receiving end in (MVAr)
1	2	3	4	5
1	0	.44	466	
	20	.62	656	
	40	.84	890	
	50	.95	1008	
	70	1.24	1312	400
2	0	.60	636	
	20	.78	826	
	40	1.0	1060	
	50	1.13	1198	50
	70	1.45	1539	600
3	0	.72	763	
	20	.88	934	
	40	1.10	1164	20
	50	1.24	1315	100
	70	1.64	1740	800

= 1.28 P/KWh.

(2) Transformer, errection cost is 20% capital cost,

Maximum Demand = 635 MW + 10% reserve capacity

= 700 MW

Size of Transformer = 2 Nos. of 500 MVA + 2 Nos.of 200MVA

(for both ends)

Cost of Transformer = 2 x (₨.56,50,000 + ₨.46,32,920)

= ₨.205,65,840.

∴ Total capital cost = 205,66,840x 1.2

Annual charge/KWhr. = $\frac{205,65,840 \times 1.2}{33.5 \times 10}$

4

= 0.0616 P/KWhr.

(3) <u>Cost of Circuit Breakers</u>:

Capital cost = 14 x 33,60,000

Annual Charge = $\frac{14 \times 33,60,000 \times .1}{33.4 \times 10^{8}}$

= 0.141 P/KWhr.

(4) <u>Cost of Series Capacitors</u>:

I, line current/phase = $\frac{635 \times 10^{3}}{2 \times 1.73 \times 400}$

= 458 amps.

Current through the capacitor = 458 x 2

= 916 amps.

Series capacitor's rating = $I^{2} X_{C}$

= $(916)^{2} \times 24$

= 20.1 MVAr

Total series capacitor rating = 3 x 20.1

= 60.3 MVAr.

Cost of series capacitor = ₨.100 x 60.3 x 10^{3}

Table No.A-1.4 contd.

1	2	3	4	5
4	0	.80	898	
	20	.95	1008	
	40	1.16	1229	50
	50	1.32	1400	200
	70	1.75	1851	820
5	0	.83	879	
	20	1.0	1060	20
	40	1.22	1290	90
	50	1.38	1460	220
	70	1.82	1929	1000

A-1.4. Sample calculation for the cost of Transmission of per unit energy:

Method 1:

Number of Intermediate sub-station 1,

Series capacitor compensation 20%

Power transferred at the transient stability limit=635 MW.

Average power, at 60% load factor = .6 x 635

= 382 MW

Energy supplied per annum = $382 \times 8760 \times 10^3$

= 33.4×10^8 KWh.

(1) Cost of Transmission Line:

Capital cost = 8,91,000 x 480

= ₨. 428×10^6.

$$\therefore \text{Annual charge/KWhr} = \frac{428 \times 10^6 \times .1}{33.4 \times 10^8}$$

∴ Annual charge $= \dfrac{100 \times 10^3 \times 60.3 \times .1}{33.4 \times 10^8}$

$= 0.0175$ P/KWhr.

(5) <u>Power Loss</u>

$I^2R_L = 6 \times (458)^2 \times 24$

$= 30.2$ MW.

Annual Power Loss due to corona = 4 MW

Total annual power loss = 30.2 + 4

=34.2 MWs.

Annual Demand Charge = ₨.1200 x 34.2 x 10^3

∴ Annual charge $= \dfrac{1200 \times 34.2 \times 10^3 \times .1}{33.4 \times 10^8}$

$= 0.103$ P/KWhr.

Energy loss at 40% loss factor $= .4 \times 30.2 \times 8760 \times 10^3$ KWhr.

Total energy per annum $= (30.2 \times .4 + 4) \times 8760 \times 10^3$ KWhr.

Cost of energy loss $= \dfrac{16.08 \times 8760 \times 5.5}{33.4 \times 10^8}$

$= 0.232$ P/KWhr.

(1) Transmission line = 1.28 P/KWhr

(2) Transformer ... = 0.0616 P/KWhr

(3) Circuit Breakers = 0.141 P/KWhr

(4) Series Capacitor = 0.0175 P/KWhr

(5) Line Loss .. =

(a) Demand Charge = 0.123 P/KWhr.

(b) Energy charge = 0.232 P/KWhr.

Total cost of Transmission of Energy-- = 1.825 P/KWhr.

TABLE NO.A-1.5

Method 1

Cost per unit of energy transmission obtained by method I

% of series comp.	No.of s/s 1 Cost of Trans. P/KWhr	No.of s/s 2 Cost of Trans. P/KWhr	No.of s/s 3 Cost of Trans. P/KWhr	No.of s/s 4 Cost of Trans. P/KWhr	No.of s/s 5 Cost of Trans. P/KWhr
0	2.216	1.895	1.826	1.793	1.759
20	1.825	1.715	1.665	1.663	1.71
40	1.645	1.587	1.565	1.59	1.676
60	1.570	1.601	1.606	1.617	1.704
70	1.621	1.631	1.698	1.761	1.77

TABLE NO.A-1.6

Method 2

Cost per unit of energy transmission obtained by method 2.

% of series Comp.	No.of s/s 0 Cost of Trans. P/KWhr	No.of s/s 1 Cost of Trans. P/KWhr	No.of s/s 2 Cost of Trans. P/KWhr	No.of s/s 3 Cost of Trans. P/kWhr	No.of s/s 4 Cost of Trans. P/KWhr	No.of s/ 5 Costof Trans. P/KWhr
20	2.487	1.919	1.711	1.692	1.736	1.752
40	2.05	1.707	1.721	1.765	1.804	1.835
60	1.747	1.824	1.94	1.863	2.05	2.05
70	1.884	2.102	2.262	2.2	2.325	2.385

TABLE NO.A-1.7

Method 3

Cost per unit of energy transmission
by method 3.
3-Intermediate Substation is considered

% of series Comp.Excess reactance	Initial Comp 12.5% Cost of Trans P/KWhr	Initial Comp 25% Cost of Trans P/KWhr	Initial Comp 50% Cost of Trans P/KWhr	Initial Comp. 75% Cost of Trans. P/KWhr
0	1.849	1.879	1.848	1.814
20	1.748	1.67	1.659	1.727
40	1.688	1.644	1.633	1.76
60	1.67	1.649	1.65	1.84
80	1.635	1.649	1.706	1.969
100	1.606	1.648	1.816	2.207

TABLE NO.A-1.8

Method 4

Cost per unit of energy transmission
by method 4.
With 30% Compensation in the Busbars

% of series Comp.	No.of s/s 1 Cost of Trans. P/KWhr	No.of s/s 2 Cost of Trans. P/KWhr	No.of s/s 3 Cost of Trans. P/KWhr	No.of s/s 4 Cost of Trans. P/KWhr	No.of s/s 5 Cost of Trans. P/KWhr
0	2.227	1.98	1.855	1.788	1.873
20	1.894	1.762	1.739	1.773	1.837
40	1.702	1.717	1.754	1.805	1.845
50	1.705	1.755	1.81	1.866	1.937
70	1.900	1.986	2.109	2.194	2.257

APPENDIX 2

A-2.1 Effect of Capacitive Fault on Directional Relays:

A-2.1.1. For 30° Connection-

A vector diagram is shown in Fig.(4.1c) for 30° relay connection. Due to capacitive fault, fault current I_L will lead by an angle ϕ_L. Therefore the torque developed in the relay is given by the following equation.

$$T = K' V_{ac} . I_L \cos(\phi_r + \alpha)$$

$$T = K' V_{ac} . I_L \cos(30 + \phi_L - \alpha),$$ putting the value of ϕ_r

(1) For internal relay angle $\alpha = 30^\circ$

$$T = K' V_{ac} I_L \cos(30 + \phi_L - 30)$$

$$= K' V_{ac} I_L \cos \phi_L$$

$\therefore T = 0$ or -ve

for $-90^\circ \leqslant \phi_L \geqslant 90^\circ$

(2) For internal relay angle $\alpha = 60^\circ$

$$T = K' V_{ac} I_L \cos(30 + \phi_L - 60)$$

$$= K' V_{ac} I_L \cos(-30 + \phi_L)$$

$\therefore T = 0$ or -ve

for $-60^\circ \leqslant \phi_L \geqslant 120^\circ$

(3) For internal relay angle $\alpha = 90^\circ$

$$T = K' V_{ac} I_L \cos(30 + \phi_L - 90)$$

$$= K' V_{ac} I_L \cos(-60 + \phi_L)$$

$\therefore T = 0$ or -ve

for $-30^\circ \leqslant \phi_L \geqslant 150^\circ$

A-2.1.2. <u>For 60° Connection</u>:

The vector diagram is shown in Fig.(4.1d). The torque equation for capacitive fault current will be given as follows;

$$T = K' V_I I_L \cos (\phi_L + \alpha)$$

$\therefore T = K' V_I I_L \cos (\phi_L + 60 - \alpha)$ putting the value of ϕ_r.

(1) For internal relay angle $\alpha = 30°$,

$$T = K' V_I I_L \cos (60 + \phi_L - 30)$$

$$= K' V_I I_L \cos (30 + \phi_L)$$

$\therefore T = 0$ or -ve

for $-120° \leqslant \phi_L \geqslant 60°$

(2) $\alpha = 60°$

$$T = K' V_I I_L \cos (60 + \phi_L - 60)$$

$$= K' V_I I_L \cos \phi_L$$

$\therefore T = 0$ or -ve

for $-90° \leqslant \phi_L \geqslant 90°$

(3) $\alpha = 90°$

$$T = K' V_I I_L \cos (60 + \phi_L - 90)$$

$$= K' V_I I_L \cos (-30 + \phi_L)$$

$\therefore T = 0$ or -ve

for $-60° \leqslant \phi_L \geqslant 60°$.

APPENDIX 3

A.3.1. Application of Proposed Mho Relay Scheme:

For system shown in Fig.(A-3.1a), the series capacitor is located at distance $\frac{1}{4}$th of the total length of the line from the sending end, and percentage of compensation given is 50%. In Fig.(A-3.1b) $ACDB_1$ and ACB are the line impedances with and without the series capacitor respectively.

The protection of the line with polarised relay is given as follows.

Z_L = line impedance = .15 + j .6 p.u.

Z_S = Source impedance = j .42 p.u.

X_C = Series Capacitor reactance = -j.3 p.u.

The inputs to the static phase comparators are-

$$S_1 = -K_1 V_L + I_L Z_{R1} \underline{/ \theta_1 - \phi_L}$$

$$S_2 = K_2 V_L + I_L Z_P \underline{/ \theta_P - \phi_L}$$

For Relay M1

Z_{R1} = Replica impedance = .15 + j.6 -j.3 = .15 +j.3 p.u.

$K_1 = 1\angle 0^{\circ}$ (assumed)

$\therefore Z_{R1}/K_1 = .15 + j.3$

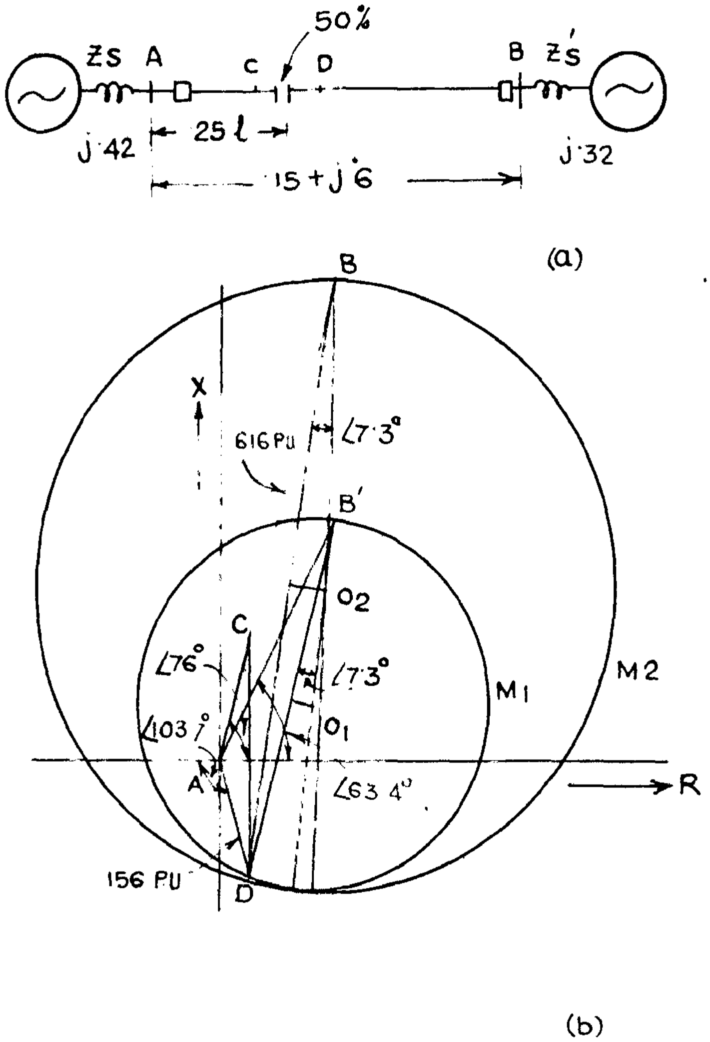
$$K_2 = K_2' + \frac{1}{\sqrt{3}} K_{YB}$$

assumed values:

$K_2' = 1\angle 0^{\circ}$

$K_{YB} = 1\angle 20^{\circ}$, and 20° phase shift is given to V_R w.r.t. V_{YB} (

$$\therefore \quad K_2 = K_2' + \frac{1}{\sqrt{3}} K_{YB}$$



(a)

(b)

SCALE 1CM = 1 PU.

FIG. A3.1 PROTECTION OF TIE LINE WITH MODIFIED Mho RELAY SCHEME

$$= 1 \angle 0^\circ + \frac{1}{1.73} \cdot 1 \angle 20^\circ$$

$$= 1 + .577 (.94 + j.342)$$

$$= 1 + .542 + j.1972$$

$$= 1.542 + j.1972 = 1.55 \angle 7.3^\circ$$

$$Z_P = \frac{1}{\sqrt{3}} \cdot K_{YB} \cdot Z_S \angle \theta_S + \theta_{YB}$$

$$= \frac{1}{1.73} \times 1 \times .42 \angle 90 + 20$$

$$= 0.242 \angle 110^\circ$$

$$\therefore \frac{Z_P}{K_2} = \frac{.242}{1.55} \angle 110 - 7.3 = .156 \angle 103.7^\circ$$

For Relay M_2

$$Z_{R1} = .15 + j.6$$

$$K_1 = 1 \angle 0^\circ$$

$$\therefore Z_{R1}/K_1 = .15 + j.6$$

$$Z_P/K_2 = .156 \angle 103.7^\circ$$

With the help of this datas relay characteristics can be plotted in R-X plane as shown in Fig.(A-3.1b)

A-3.2. Application of Quadrilateral Relay Characteristic:

The system shown in Fig.(A-3.2a) is considered. The series capacitor is located at the sending end and percentage of compensation is assumed to be 75%.

In Fig.(A-3.2b), ADB' is the line impedance with series capacitor in the circuit whereas AB is the line impedance without the series capacitor.

The quadrilateral relay characteristic LMNP is used to protect the line with and without the series capacitors. The relay characteristic is obtained as follows.

The comparator No.1 gives the relay characteristic LMN and comparator No.2 gives characteristic LPN shown shaded in Fig.(A-3.2). The combination of the two gives the required relay characteristic.

Input to the comparator No.1 is S_1 and S_2

where,

$$S_1 = - K_1 \angle \alpha_1 \; V_L + I_L \, Z_{R1} \angle \theta_1 - \phi_L$$

$$S_2 = I_L \, Z_{R2} \angle \theta_2 - \phi_L$$

For the system,

$$Z_L = \text{Line impedance} = .147 + j.6 = .618 \angle 78^\circ .$$

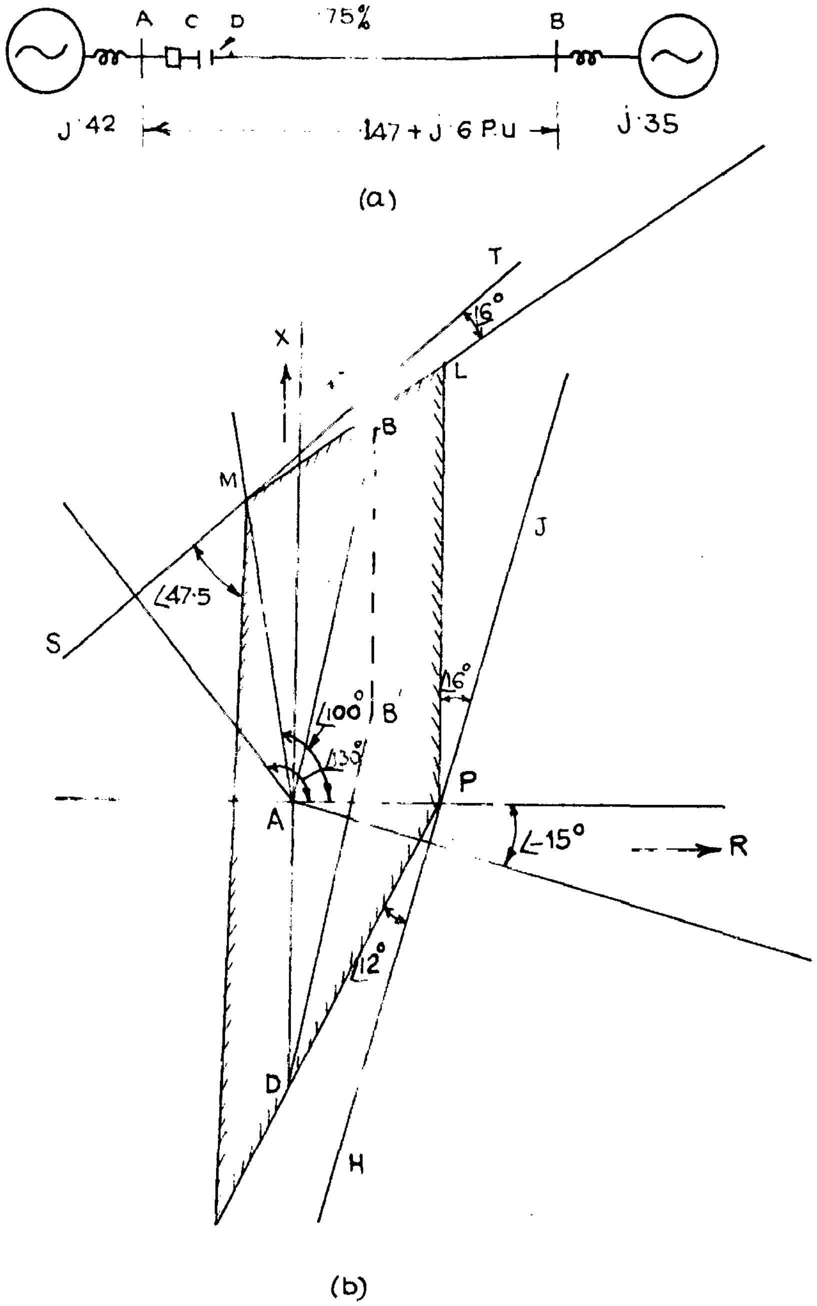
Following values are assumed,

$$K_1 \angle \alpha_1 = 1 \angle -50^\circ \qquad Z_{R1} \angle \theta_1 = .495 \angle 50^\circ$$

$$Z_{R2} \angle \theta_2 = .248 \angle 80^\circ$$

$$\therefore \frac{Z_{R1} \angle \theta_1 - \alpha_1}{K_1} = \frac{.495}{1} \angle 50 + 50 = .495 \angle 100^\circ$$

$$\therefore \angle \theta_2 - \alpha_1 = 80 + 50 = 130^\circ$$



SCALE : 1 CM = ·126 P.U.

FIG. A3. 2 QUADRILATERAL CHARACTERISTIC.

From Fig.(A-3.2b)-

$\angle 90 - \beta_1 = 6^\circ$ and $\angle 90 - \beta_2 = 47.5^\circ$

$\therefore \angle \beta_1 = 84^\circ$ $\qquad \angle \beta_2 = 42.5^\circ$

To obtain the desired relay characteristic, the comparator must satisfy the equation (5.5) and (5.6) as shown below.

$$K_1 Z_L \cos(\theta_2 - \alpha_1 - \phi_L) + Z_{R1} \cos(\theta_2 - \theta_1)$$

$$= .618 \cos(130 - 78) + .495 \cos(80 - 50)$$

$$= .618 \cos 52 + .495 \cos 30$$

$$= .381 + .429 = .800.$$

$$-\cot \beta_1 [K_1 Z_L \sin(\alpha_1 - \theta_2 + \phi_L) + Z_{R1} \sin(\theta_1 - \theta_2)$$

$$= -\cot 84 [.618 \sin(-130 + 78) + .495 \sin(-30)]$$

$$= \cot 84 (.618 . \sin 52 + .495 \sin 30)$$

$$= \cot 84 (.486 + .248) = \frac{.734}{9.514}$$

$$= .077$$

Again,

$$\cot \beta_2 [K_1 Z_L \sin(\alpha_1 - \theta_2 + \phi_L) + Z_{R1} \sin(\theta_1 - \theta_2)]$$

$$= \cot 42.5 (-.618 \sin 52 - .495 \sin 30)$$

$$= -\cot 42.5 \times .734 = - \frac{.734}{.916}$$

$$= -.8$$

Hence comparator No.1 satisfies both the relations.. Therefore the required relay characteristic can be obtained.

For comparator No.2 Inputs S_3 and S_4 are given by

$$S_3 = -K_3 \angle \alpha_3 V_L + Z_{R3} I_L \underline{/\theta_3} - \phi_L$$

$S_4 = Z_{Ra} I_L \underline{/\theta_4 - \phi_L}$

Following values are assumed,

$K_3 \underline{/\alpha_3}' = 1 \underline{/70^\circ}$

$Z_{R3} \underline{/\theta_3} = .248 \underline{/70^\circ}$

$Z_{R4} \underline{/\theta_4} = .248 \underline{/55^\circ}$

$$\therefore \frac{Z_{R3} \underline{/\theta_3 - \alpha_3}}{K_3} = .248 \underline{/70 - 70} = .248 \underline{/0^\circ}$$

$\underline{/\theta_4 - \alpha_3} = \underline{/55^\circ - 70^\circ} = \underline{/-15^\circ}$

From Fig.(A-3.2b),

$\underline{/90} - \beta_3 = 16^\circ, \qquad \underline{/90} - \beta_4 = 12^\circ$

$\therefore \underline{/\beta_3} = 74^\circ \qquad \underline{/\beta_4} = 78^\circ$

This comparator also have to satisfy the equation (5.9) and (5.10) as shown below.

$K_3 Z_L \cos(\theta_4 - \alpha_3 - \phi_L) + Z_{R3} \cos(\theta_4 - \theta_3)$

$= .618 \cos(-15^\circ - 78) + .248 \cos(55-70)$

$= .618 \cos(-93) + .248 \cos(-15)$

$= -.0323 + .24 = .208$

$- \cot \beta_3 [K_3 Z_L \sin(\alpha_3 - \theta_4 + \phi_L) + Z_{R3} \sin(\theta_3 - \theta_4)]$

$= -\cot 74^\circ (.618 \sin 93^\circ + .248 \sin 15)$

$= -\cot 74^\circ (.617 + .0643)$

$= - \frac{.6813}{3.487} = \underline{-.195}$

Again,

$$\cot \beta_4 \left[K_3 Z_L \sin(\alpha_3 - \theta_4 + \Delta_L) + Z_{R3} \sin(\theta_3 - \theta_4) \right]$$

$$= \cot 78\,(.6813) = \frac{.6813}{4.7} = .14$$

Hence both the conditions are satisfied for the required relay characteristic.

The final relay characteristic will be obtained by combining the output of the two comparators with the help of an 'AND' gate.

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