

SERIES COMPENSATION FOR EXTRA HIGH VOLTAGE LINES

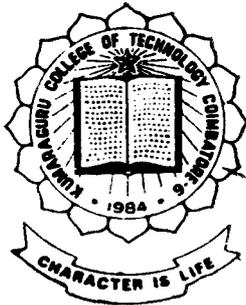
PROJECT REPORT

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OF THE DEGREE OF BACHELOR OF ENGINEERING IN ELECTRICAL AND ELECTRONICS
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This is to certify that the Report entitled
Series Compensation for Extra High Voltage Lines
has been submitted by

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in partial fulfilment for the award of Bachelor of Engineering
in the Electrical and Electronics Engineering Branch of the
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SYNOPSIS

This project work envisages the manifestation for extra high-voltage transmission, both high voltage AC and high voltage DC have been considered taking into account and postulating the draw backs and efficacious results. The crying need of the hour seems to be, an efficient power transfer ability. Profuse Analysis of the various types of compensation schemes aptly suitable for EHV lines is dealt in Chapter II.

Chapter III gives the new suggestive ideologies, achieving optimum compensation at the sending end of the transmission line to yield maximum received power.

Chapter IV portrays, the HVAC - HVDC links and its vantage capability to increase overall stability.

Over voltage Criterion in HVAC and HVDC transmission system is dealt in Chapter V with considerable endeavours to attain certain amount of negligence on this aspect.

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INTRODUCTION

Development of sources of energy to accomplish useful work is the key to the industrial progress which is essential to the continual improvement in the standard of living of people everywhere. To discover new sources of energy, to obtain an essential supply of energy for future, to make energy from one form to another without polluting the atmosphere are the greatest challenges facing the world today. The electrical power system is one of the tools for converting and transporting energy which is playing an important role in meeting this challenge.

An electric power systems consists of three principal divisions the generating stations, the transmission lines, and the distribution systems. The transmission lines are the connecting links between the generating stations and the distribution systems and lead to other power systems over inter connection.

The generator voltage is stepped upto transmission levels in the range of 115 to 765 KV. They can be categorized as High Voltage (HV) and Extra High Voltage (EHV) voltages of 330 KV and above fall in EHV category. In India, 400 KV A.C. transmission system are in service in several systems. The behaviour of this EHV lines is in many respects simillar to 220 KV lines.

Transmission of large blocks of power over long distances can be done most economically only using EHV lines, normally EHV A.C is preferred. In intial stages DC was used for electric power transmission. This was largely due to ease of control and also because DC motors

were the only satisfactory electromechanical A.C converters. But gradually A.C has replaced D.C due to following factors.

- i) For a given amount of power to be transmitted over a given distance, as the transmission voltage increases the transmission efficiency increases and also the percentage resistance drop decreases.
- ii) The power transmission capacity of a transmission line is proportional to the square of the operating voltage. Hence the overall transmission cost decreases.
- iii) Economic considerations have led to construction of super power stations of very large capacities.

Extra High Voltage transmission technique have many technical and economic advantages for transmitting bulk power over large distance which are listed below :

- i) At doubled voltage a transmission circuit can carry approximately twice as much power as the same circuit.
- ii) At doubled voltage a transmission circuit can carry approximately four times as much power at the same percentage voltage regulation and percentage loss.
- iii) At doubled voltage a transmission circuit can carry from two to four times as much power with the same degree of stability.

Thus technically advantageous E.H.V. transmission have improved stability, voltage regulation and reduction in electrical losses.

Along with the technical advantages the use of EHV transmission has also many economic advantages. Some of the economic factors favourable to the use of EHV transmission are :

- i) Maximum utilisation of available rights say in areas where available routes are limited in number and cost.
- ii) Maximum feasibility for future system growth.
- iii) Savings in money due to lower transmission losses for a given load requirements.

In case of EHV power transmission the use of bundle conductors technique is used. The bundling of conductor per phase, in EHV lines two, three or four conductor bundles have been used. The spacing between the conductors of an individual bundle is kept constant throughout the length of the line with the help of spacers. The spacing between the conductors of bundle varies from 20cms to 60cms, depending on different voltage and surrounding conditions.

The bundle conductors have many advantages over single conductor in EHV transmission which are stated as follows ;

- i) The bundle conductor transmit bulk power with minimum losses. So efficiency is higher.
- ii) The inductance per phase is less resulting into lower

reactance which plays an important part in determining the power rating of the line as both drop and stability limit of the load depends principally on reactance.

iii) The bundle conductor lines have a higher capacitance to neutral than single conductor lines. The lower reactance increases the charging current which helps in improving the power factors.

iv) A bundle conductor considerably reduces the line inductance and increases the capacitance per phase, it results in the surge impedance (z) of the line.

OBJECTIVE OF COMPENSATION :

The performance of the transmission lines, especially those of medium length and longer, can be improved by reactive compensation of a series or parallel type.

Shunt compensation refers to the placement of inductors from each line to neutral to reduce partially or completely the shunt susceptance of a high voltage line, which is particularly important at light loads when the voltage at the receiving end may otherwise become high.

In series compensation, series capacitors are installed in series with long transmission lines transmitting large blocks of power. These capacitors are installed either at the middle of the line or near one of the ends near the terminal station. The basic purpose of the series

capacitor is to increase the steady state and transient stability limits by reducing the total reactance between the two ends of the line. The series capacitors provide compensation i.e., they compensate the inductive reactance of long lines. The compensation is said to be 50% when the series capacitive reactance X_c exceeds is 50% the inductive reactance of the line.

Series capacitors have posed some trickiest problems in power systems. The sub resonance has resulted in failure of rotor shafts of synchronous generators and have given rise to odd harmonics and ripples in voltage and current wave forms.

The main advantage of using series compensation the equation ' $X' = X - X_c$ ' is reduced thereby the power transferability of the line is increased. This is basically series compensation. Thus the series compensation reduces the series impedance of the line, which is the principal cause of voltage drop and the most important factor in determining the maximum power which the line can transmit.

CHAPTER - I

HIGH VOLTAGE AC AND HIGH VOLTAGE DC TRANSMISSION

CORONA IN CASE OF EHV LINE

It is of great significance in EHV transmission as it seriously affects the performance of the line. So it is of considerable economic importance to keep these losses to a low value. It is quite difficult to estimate corona losses with reasonable accuracy because such losses are extremely dependent on weather conditions, and so attempts are directed to reduce corona losses in lower range of extra high voltages. However the best performance from the corona loss point of view can be viewed in EHV transmission lines, only by using bundle conductor. The visual corona voltage at which it becomes visible is raised by bundling. The start of the phenomena of the corona and corona loss depends on voltage gradient at the surface of the conductor. The voltage gradient is not uniform in case of bundle conductor but it is very much reduced. The reduction varies from 5% to 15%. This factor is mainly responsible for the reduction of corona losses in bundle conductor.

RADIO INTERFERENCE

The bundle conductors kept at radio interference in thin limits. Radio interference is generated by the ionization of air in an intensive electric field and depends upon the intensity of electric gradient on the conductor surface. Radio interference levels are the highest at the lower frequency and radio interference decreases with increase of frequency being least or negligible at higher frequencies. The radio interference properties of transmission line conductor can be judged by the radio influence voltage generated on the conductor surface. Radio influence voltage is the radio frequency voltage that exists between the

conductor and ground as a result of corona discharges and it is measured in micro volts at a frequency of 1000 kilo cycles/sec. The visual corona voltage, the radio influence voltage is negligibly small but with the initial appearance of corona the radio influence voltage level increases rapidly reaching very high values for small increases above the visual corona voltages. Bundle conditions produce lower radio interference level than comparable single conduction.

The limitations on the amount of power transmission on a over head line is controlled with certain load factor over certain distances. The power depends on the current, voltage, power factor and number of conductors.

CURRENT LIMIT

The temperature of the conductor must be limited in order to avoid damage to the conductor itself. Hence the amount of current in conductor must be limited.

VOLTAGE LIMIT

On EHV overhead linear switching surges, rather than lightning have become the more surges transient over voltage and on A.C. lines attempts are made to limit these to peak value of two or three linear coaxial exert voltage, switching surges, on D.C lines are more than this, say 1.7 times normal voltage,

STABILITY

By the stability of an AC systems is meant its stability to

operate with all synchronous inactive in synchronous. If an A.C. system is used with a D.C link will not have any stability problems. The operation of an A.C line with ground reference is not feasible on account of high impedance of such circuit and the interferences caused by such operation.

Another mode of bulk transmission of power can be by the use of HVDC transmission since it requires only two conductors for the same power capability and comparable reliability but that cost of terminal equipment of the HVDC line is much more than that of HVDC systems. If the transmission distance is less than the over distance AC transmission is cheaper than D.C if longer D.C is cheaper than A.C.

ADVANTAGES OF HVDC TRANSMISSION

1. Greater power per conductor
2. Simple line construction.
3. Ground reference can be used.
4. Hence each line can be operated as individual circuit.
5. No charging current.
6. No skin effect
7. Cables can be worked at a higher voltage gradient.
8. Line power factor is always one. Like does not require reactive compensator.
9. Less corona loss and radio interference.
10. Synchronous operation is not required.
11. May inter connect AC of different frequencies.
12. Low short circuit current on D.C liner
13. Transmissionline power can be easily controlled.

DISADVANTAGES OF HVDC TRANSMISSION

1. Convertors are in expensive
2. Convertors require much reactive power.
3. Convertors generate harmonics, requiring filter.
4. Convertors have limited over head capacity.

CHAPTER 2

COMPENSATION SCHEMES

SHUNT AND SERIES COMPENSATION :

In EHV Lines, the use of series capacitors in conjunction with lines has become common since it offers an economic and effective means of improving stability limits and thus permits the lines to carry more power. Series capacitors also regulate automatically the reactive power and can be used to give an ideal load distribution between lines working in parallel having different reactance to resistance ratio. The proper use of shunt reactors with series capacitor limits the power frequency over voltages and increases maximum power transfer. In EHV lines the use of shunt reactors reduces the capacitive generation effect of the line while series capacitors reduces the series reactance of the line. When both shunt and series compensations are provided on such lines, the over voltages under steady state and during load rejection are reduced and the power capability of the line is enhanced.

For measuring the effectiveness of a series capacitor compensation efficiency defined as the ratio of net reduction in transfer reactance to the series capacitor reactance used. For a compensated line the compensation efficiency indicates the effectiveness of series capacitors in reducing the transfer impedance of that line. The compensation efficiency is usually less than one and is the index of increase in power carrying capability of line by the use of series capacitors.

For a line having only series compensation, the compensation efficiency is maximum when it is located at the centre of the line. The use of shunt reactors on the line modifies the compensation efficiency of the series compensated line. The best location for the series capacitor in case of a single capacitor bank is the mid-point of the line, whatever be the line length and that the effectiveness of series compensation decreases with increasing line lengths. For a higher values of series compensation, shunt compensation increases the compensation efficiency for all positions of the series capacitor for single capacitor bank.

The shunt compensation for a given degree of series compensation increases the power capability of the line and this effectiveness will be high, when the capacitor and reactor are placed at either end of the line.

When sending end and receiving end voltage on a line are held constant, under no load condition a series capacitor bank located at the middle of the line does not affect the voltage profile of the line. When the capacitor line is located at the middle of the line two reactors located one each at the terminal of the capacitor to give the minimum reactor rating for limiting the maximum power frequency over voltage. The above effect can also be achieved with a single reactor located at a terminal of the capacitor but with a much higher rating in comparison with the two reactance one each at the terminal of the capacitor. When the capacitor bank is shifted from the middle of the line either towards sending or receiving end it is most desirable to have two reactors, one located at each terminal of the capacitor to limit

the over voltage. The rating of each reactor is so chosen that the maximum over voltage on each section of the line can be controlled independently within the permissible limit.

In EHV systems capacitive generation of the line poses problems during line charging, operating at low loads and switching operations (including load rejections) causing an undesirable voltage rise on the line. Shunt reactors (both fixed and dynamic) with their capability to compensate. The capacitive generation effect of the line provide an economical and technically sound means to control these voltage rises. EHV lines at 400 KV are generally series compensated because series capacitors increase the stability limit, giving the load transmission lines a greater power carrying capacity. They can be used to give an ideal load distribution between lines working in parallel having different reactance to resistance ratio.

When both series and shunt compensations are used on EHV lines, there is sufficient interaction between the individual effects of each type of compensating element on the performance of the line. When planning long distance EHV transmission lines, it is necessary to determine not only the average degrees of compensation required but also the most appropriate location of reactors and capacitor banks, the optimal connection scheme and the number of intermediate stations. The application of capacitors and reactors at line terminals have better advantages of switching and control because these stations are always attended.

A suitable scheme of shunt and series compensation can be

choosenkeeping in view the compensation efficiency scheme and system effectiveness, voltage profile along the line during steady state condition and over voltage occurring in the line during switching operations including load rejection.

The different compensation schemes are shown in Figure 1. The schemes of Fig. 1(A) to 1(E) are symmetrical, while 1(F) and 1(G) are non-symmetrical. Compensation efficiencies of various schemes of Fig 1 are expressed by :

$$\eta_A = \left(\frac{X_C}{4} \right) \sin \beta_0 l + \cos \beta_0 l \quad (1)$$

$$\eta_B = \left(\frac{Y + X_C}{4} - \frac{Y^2 + X_C}{4} \right) \sin \beta_0 l + \left(\frac{1 - YX_C}{2} \right) \cos \beta_0 l \quad (2)$$

$$\eta_C = \cos^2 \frac{\beta_0 l}{2} \quad (3)$$

$$\eta_D = 2Y \sin \beta_0 l/2 \cos \beta_0 l/2 + \cos^2 \beta_0 l/2 - 2(Y/X_C - Y^2) \sin^2 \beta_0 l/2 \quad \dots \dots (4)$$

$$\eta_E = (\cos \beta_0 l/2 + Y \sin \beta_0 l/2)^2 - (2 Y/X_C) \sin^2 \beta_0 l/2 \quad (5)$$

$$\eta_F = \cos \beta_0 l \quad \dots \dots (6)$$

$$\eta_G = \cos \beta_0 l + Y \sin \beta_0 l \quad \dots \dots (7)$$

Where Y is the per unit value of each reactor in the scheme and X_C is the per unit value of the series compensation in the scheme.

Figure 2 shows the variation of compensation efficiency of various symmetrical schemes as a function of series and shunt compensation for a 400 Kv line having the following constants :

Resistance = 0.0233 Ohm per K.M,
 Inductance = 0.2902 Ohm per K.M.
 Shunt admittance = 3.0246×10^{-6} mho per K.M.

SCHEME AND SYSTEM EFFECTIVENESS :

This concept is used to observe the effectiveness of capacitors and reactors in a particular compensation scheme where the compensating elements are concentrated at a few points with that of schemes where the compensation is uniformly distributed.

The scheme effectiveness (ϵ_1) is defined as :

$$\epsilon_1 = \frac{\text{Sending-end maximum transmissible power of actual system}}{\text{sending-end maximum transmissible power of idealized system with same compensations uniformly distributed.}}$$

In the same manner system effectiveness (ϵ_2) is given by

$$\epsilon_2 = \frac{\text{Sending-end maximum transmissible power of actual system}}{\text{sending-end maximum transmissible power of idealized system with uniformly distributed compensation, } K_D = 100\% \text{ and actual } K_S}$$

The ideal system considered at the denominator of index ϵ_2 is electrically equivalent to nearly the series impedance only, the shunt susceptance being nil.

For given values of K_s and K_d comparison of effectiveness index ξ_1 of various compensation schemes provides a direct assessment of the relative power transfer capabilities.

Scheme effectiveness may be above, below or equal to unity. When $\xi_1 > 1$, the stability limit of the actual system with compensation concentrated at a few points is higher than that of the ideal system with uniformly distributed compensation.

Figure - 3 shows the variation of scheme effectiveness as a function of K_d and K_s for various schemes. For a fixed degree of series and shunt compensation, scheme B has higher values of in comparison to other schemes.

In the expression of ξ_2 , the denominator is maximum power transfer capacity of the line whose shunt compensation is zero. Hence, this power depends only on the degree of series compensation and not on the scheme, the degree of shunt compensation or the length of the line section adopted.

Figure 4 shows the curves of system effectiveness as a function of K_d for various K_s values. In this scheme B is favourable over the other schemes.

From the point of view of compensation efficiency, and effectiveness indices, scheme B is the most favourable scheme.

SCHEMES OF SHUNT AND SERIES COMPENSATION

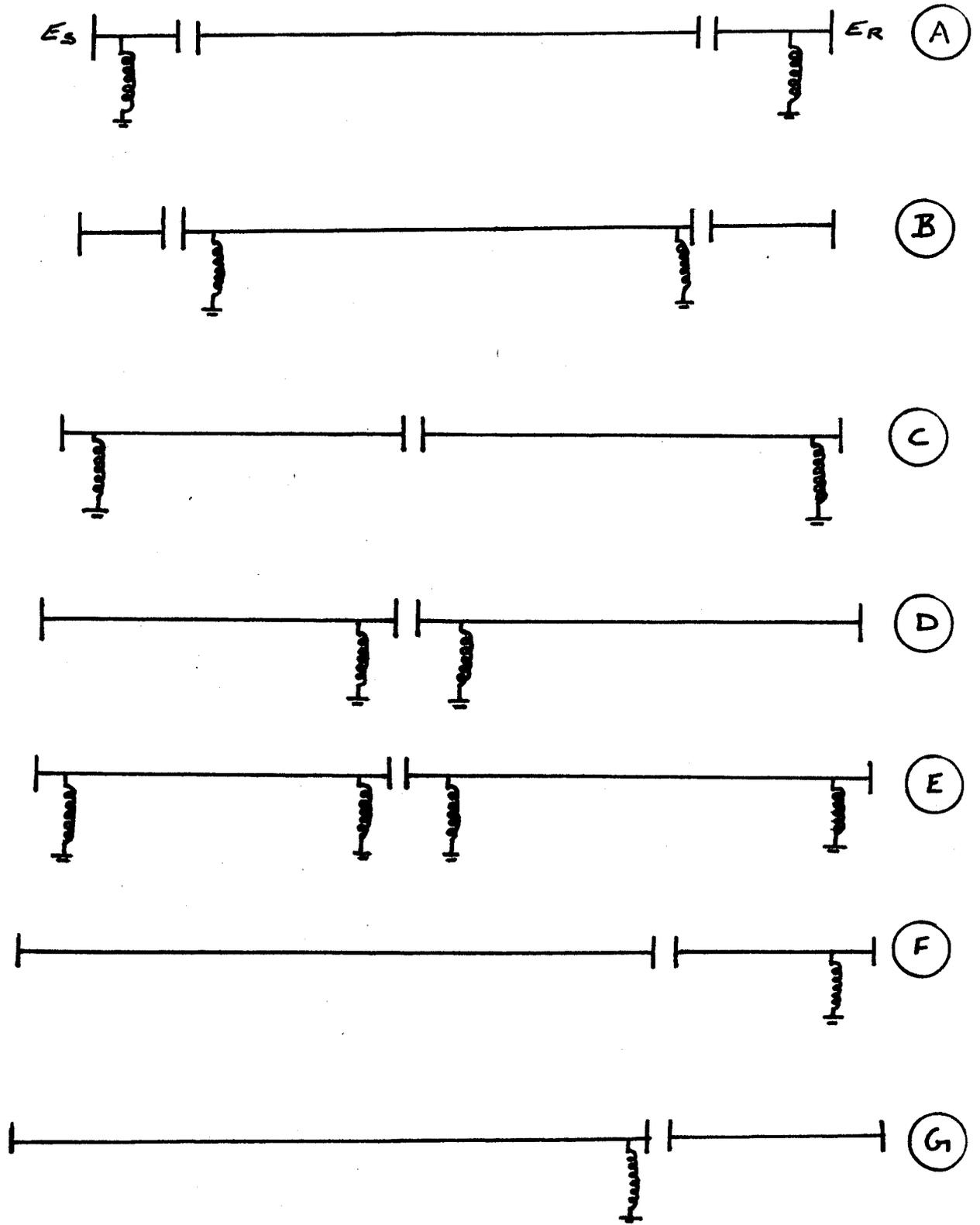


Fig 1

FIGURE - 2

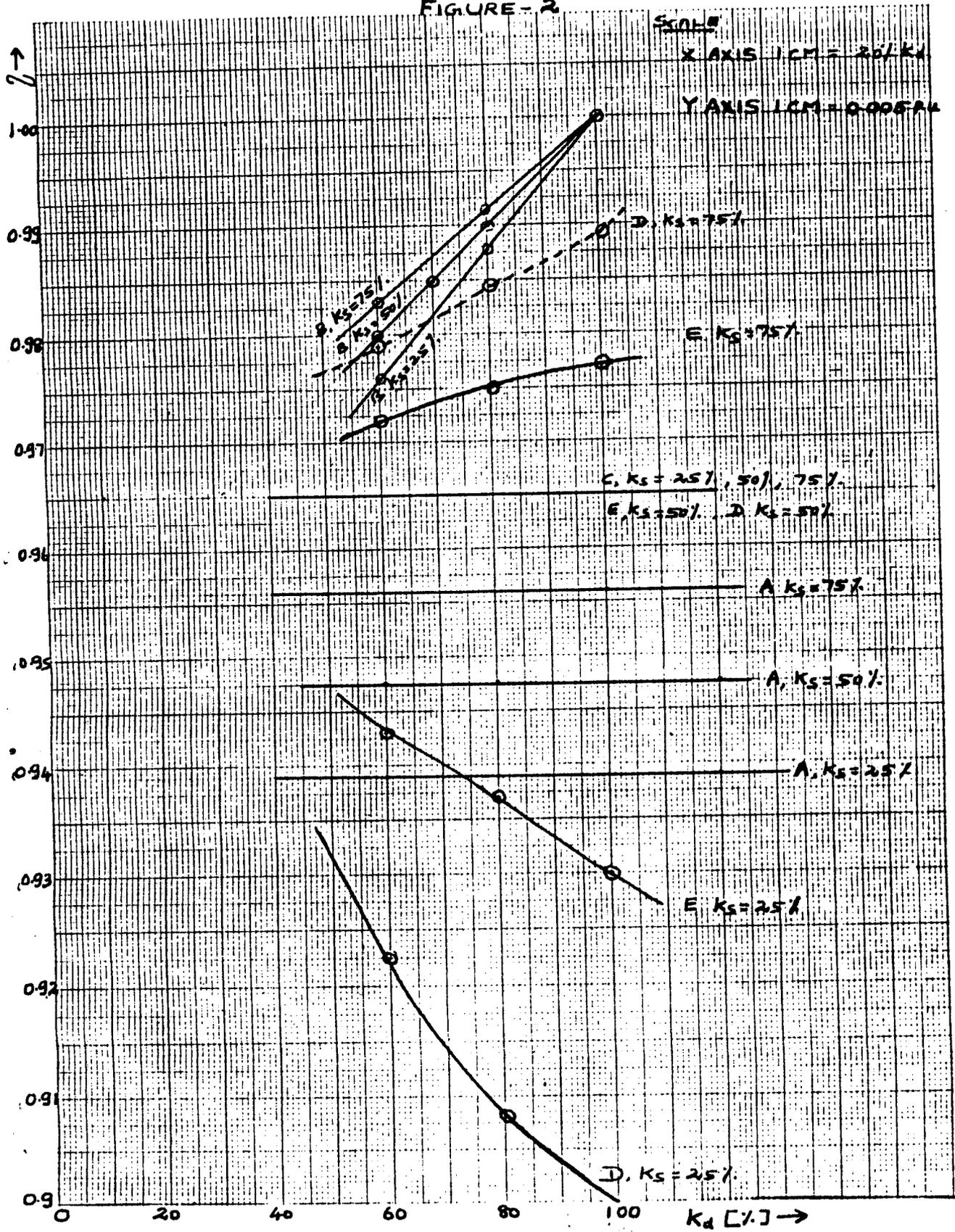


FIGURE - 3

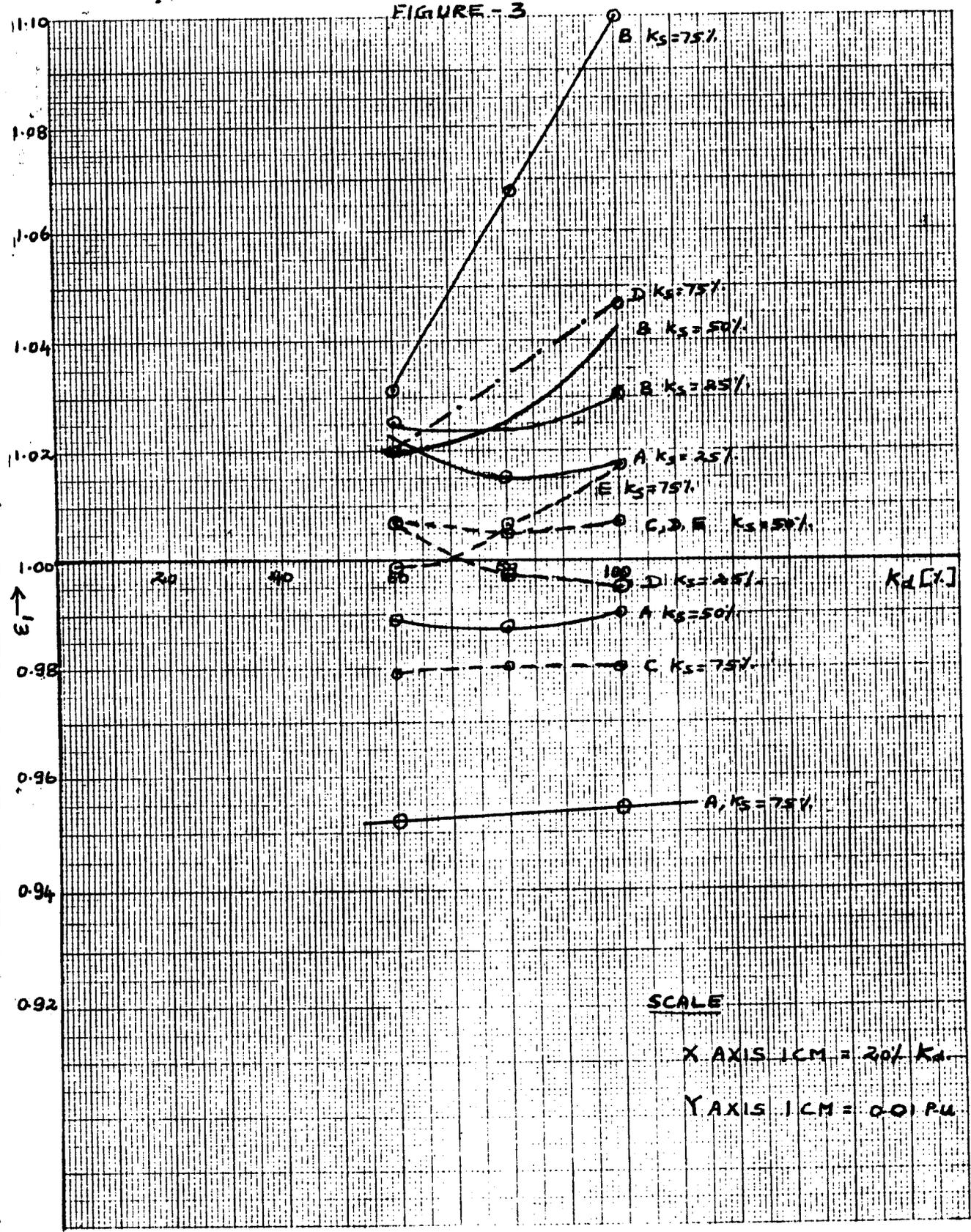
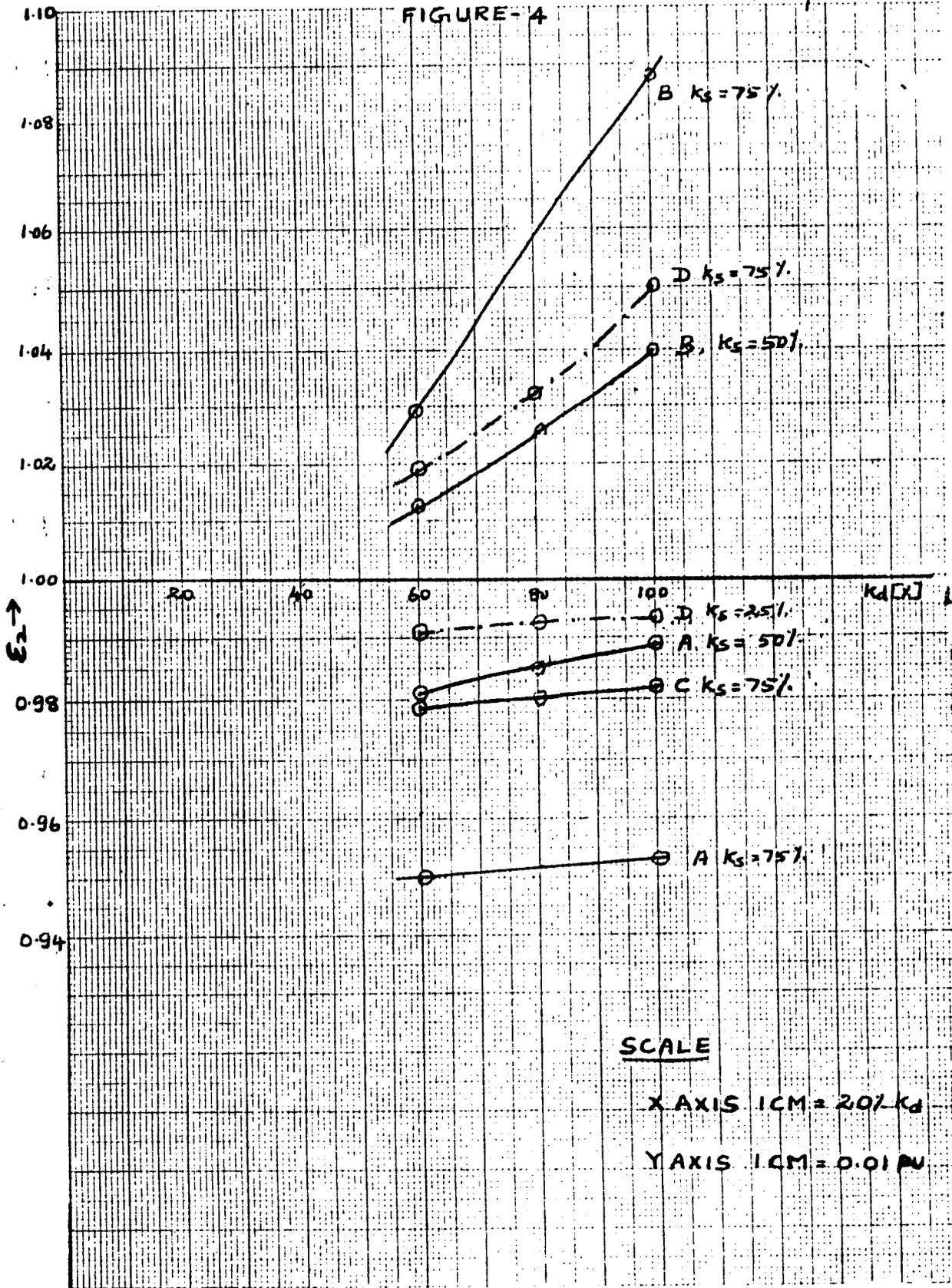


FIGURE-4



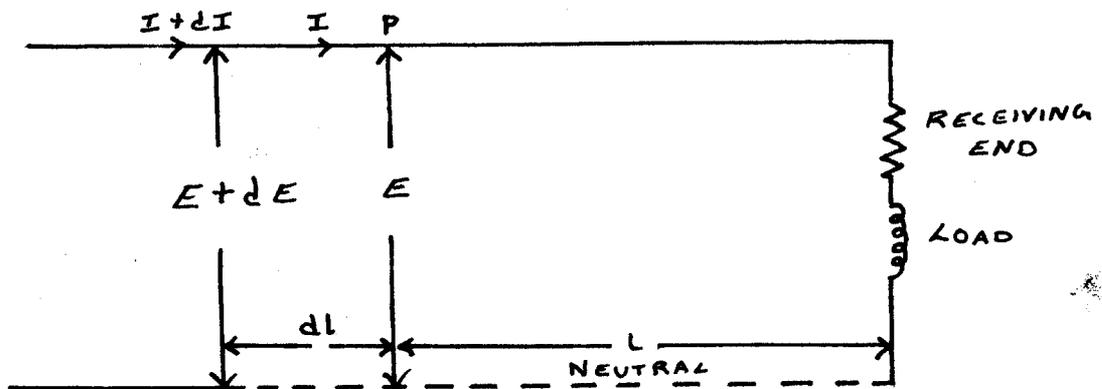
CHAPTER - 3

FUNDAMENTAL DIFFERENTIAL EQUATIONS FOR EXACT SOLUTIONS TO OBTAIN THE CONSTANTS A, B, C, D AND THE COEFFICIENT VALUES A1, A2, A3, A4 and B1, B2, B3 B4 .

Let the line be divided into an infinite number of sections and let its constants be

- r = resistance per phase per km.
 - x = reactance per phase per km.
 - g = shunt leakage conductance per phase per km
 - b = shunt leakage susceptance per phase per km
 - z = $r^2 + x^2$ impedance per phase per km
 - y = $g^2 + b^2$ admittance per phase per km
- 3.1

Let, at point P, distance l meters from the load end, the potential per phase be E volts and the current be I amperes.



Consider, small elements length dl of the line ; and let, the voltage and current at this section increase by dE and dl respectively.

The impedance z_1 and admittance y_1 for the small elemental length are given as

$$z_1 = z \times dl \quad (3.2)$$

$$y_1 = y \times dl \quad (3.3)$$

The current I in the elemental length dl will cause a drop dE in the line, so that

$$\begin{aligned} dE &= z dl \times I \\ &= Iz dl \end{aligned} \quad (3.4)$$

$$\text{or} \quad \frac{dE}{dl} = Iz \quad (3.5)$$

Current dl in the shunt leakage path

$$= E \times y dl \quad (3.6)$$

$$\text{or} \quad dl = Ey dl \quad (3.7)$$

$$\text{or} \quad \frac{dl}{dl} = Ey \quad (3.8)$$

The eqns. (14.5) and (14.8) are the fundamental equations, the solutions, of which will give the values of current and potential at the desired point.

Differentiating equation (3.5) with respect to l

$$\frac{d^2E}{dl^2} = z \frac{dl}{dl} \quad (3.9)$$

Set eqn.(3.8) in eqn. (3.9)

$$\frac{d^2E}{dl^2} = zEy \quad (3.10)$$

Similarly differentiate (3.8) with respect to l

$$\frac{d^2 l}{dl^2} = y \frac{dE}{dl} \quad (3.11)$$

Set eqn. (3.5) in eqn. (3.12)

$$\frac{d^2 l}{dl^2} = yzl \quad (3.12)$$

Multiply eqn. (3.12) by $\frac{dl}{dl}$

$$\frac{d^2 l}{dl^2} \times \frac{dl}{dl} = yzl \frac{dl}{dl} \quad (3.13)$$

Integrating both sides

$$\frac{1}{2} \left(\frac{dl}{dl} \right)^2 = \frac{1}{2} yzl^2 + C \quad (3.14)$$

where, C is a constant of integration.

$$\text{Let, } C = \frac{1}{2} yz C_1^2 \quad (3.15)$$

where C_1 is another constant

$$\frac{1}{2} \left(\frac{dl}{dl} \right)^2 = \frac{1}{2} yzl^2 + \frac{yz C_1^2}{2} \quad (3.16)$$

$$\left(\frac{dl}{dl} \right)^2 = yz (l^2 + C_1^2) \quad (3.17)$$

$$\text{or } \frac{dl}{dl} = \sqrt{yz} \left(\sqrt{l^2 + C_1^2} \right) \quad (3.18)$$

$$\text{or } \frac{dl}{\sqrt{l^2 + C_1^2}} = \sqrt{yz} \, dl \quad (3.19)$$

In order to integrate the above differential equation, let,

$$l = Q \sinh \theta \quad (3.20)$$

or $dl = Q \cosh \theta \cdot d\theta \quad (3.21)$

$$\begin{aligned} l^2 + Q^2 &= Q^2 \sinh^2 \theta + Q^2 \\ &= Q^2 \cosh^2 \theta \end{aligned} \quad (3.22)$$

or
$$\frac{dl}{\sqrt{l^2 + Q^2}} = \frac{Q \cosh \theta \cdot d\theta}{\sqrt{Q^2 \cosh^2 \theta}} \quad (3.23)$$

$$= d\theta$$

So the equation (3.19) reduces to

$$d\theta = \sqrt{yz} \, dl \quad (3.24)$$

Integration both sides

$$\theta = \int \sqrt{yz} \, dl + C_2 \quad (3.25)$$

Where C_2 is a constant of integration.

Substituting the value of θ in eqn. (3.20)

$$l = C_1 \sinh (\int \sqrt{yz} \, dl + C_2) \quad (3.26)$$

Again differentiate the above equation

$$\frac{dl}{dl} = C_1 \sqrt{yz} \cosh (\int \sqrt{yz} \, dl + C_2) \quad (3.27)$$

Substituting the value of $\frac{dl}{dl}$ in the above equation from equation(3.8)

$$Ey = C_1 \sqrt{yz} \cosh (\int \sqrt{yz} \, dl + C_2) \quad (3.28)$$

$$E = C_1 \sqrt{\frac{yz}{y^2}} \cosh (\int \sqrt{yz} \, dl + C_2) \quad (3.29)$$



$$\text{or } E = C_1 \sqrt{y/y^2} z \cosh (\sqrt{yz} + C_2) \quad (3.29)$$

$$\text{or } E = C_1 \sqrt{z/y} \cosh (\sqrt{yz} + C_2) \quad (3.30)$$

Thus, the values of current I and voltage E are given by equations (3.26) and (3.30). The values of constants C_1 and C_2 can be determined from the given conditions of the line.

Expanding equation (3.26)

$$I = C_1 (\sinh \sqrt{yz} \cosh C_2 + \cosh \sqrt{yz} \sinh C_2) \quad (3.31)$$

$$\text{When, } l = 0 \quad (3.32)$$

$$I = I_R \text{ (the receiving end current)} \quad (3.33)$$

So, rewriting eqn. (3.31) in view of eqns. (3.32) and (3.33)

$$I_R = C_1 \sinh C_2 \quad (3.34)$$

$$\text{or } \sinh C_2 = \frac{I_R}{C_1} \quad (3.35)$$

Similarly expanding equation (3.30)

$$E = C_1 \sqrt{z/y} (\cosh \sqrt{yz} \cosh C_2 + \sinh \sqrt{yz} \sinh C_2) \quad (3.36)$$

$$\text{Again for } l \text{ equal to zero} \quad (3.37)$$

$$E = E_R$$

Thus, in view of eqn. (3.37)

$$E_R = C_1 \sqrt{z/y} (\cosh C_2 + 0) \quad (3.38)$$

$$\text{or, } \cosh C = \frac{E_R}{C_1 \sqrt{z/y}}$$

Substituting the value of $\sinh C_2$ and $\cosh C_2$ in equations (3.31) and (3.36)

$$C_1 (\sinh \sqrt{yz} \times \frac{E_R}{C_1 \sqrt{z/y}} + \cosh \sqrt{yz} \times \frac{I_R}{C_1}) \quad (3.40)$$

$$\text{or } I = E_R \sqrt{y/z} \sinh \sqrt{yz} + I_R \cosh \sqrt{yz} \quad (4.41)$$

$$\text{and } E = C_1 \sqrt{\frac{z}{y}} (\cosh \sqrt{yz} \times \frac{E_R}{C_1 \sqrt{\frac{z}{y}}} + \sinh \sqrt{yz} \times \frac{I_R}{C_1}) \quad (3.42)$$

$$\text{or } E = E_R \cosh \sqrt{zy} + \sqrt{\frac{z}{y}} \sinh \sqrt{yz} I_R \quad (3.43)$$

If l is the entire length of the line, then

$$\begin{aligned} z \times l &= Z \text{ the total series impedance of the line} \\ y \times l &= Y \text{ the total shunt admittance of the line} \\ I &= I_S \text{ the sending end current} \\ E &= E_R \text{ the sending end voltage.} \end{aligned} \quad (3.44)$$

Again I and E with respect to sending end can be rewritten as:

$$I_S = E_R \sqrt{\frac{y \times l}{z \times l}} \sinh \sqrt{(y \times l)(z \times l)} + I_R \cosh \sqrt{(y \times l)(z \times l)} \quad (3.45)$$

Rewriting eqn. (3.45) in view of eqn. (3.44)

$$\text{or } I_S = E_R \sqrt{\frac{Y}{Z}} \sinh \sqrt{YZ} + I_R \cosh \sqrt{YZ} \quad (3.46)$$

$$\text{and } E_S = E_R \sqrt{(y)(z)} + I_R \sqrt{\frac{z}{y}} \sinh \sqrt{(y)(z)} \quad (3.47)$$

$$\text{or } E_S = E_R \cosh \sqrt{YZ} + I_R \sqrt{\frac{Z}{Y}} \sinh \sqrt{YZ} \quad (3.48)$$

If instead of receiving end, the sending end voltage and current are known, the the equations (3.42) and (3.43) can be used for determining the receiving end voltage and current by substituting l as $(-l)$, in which case

$$\begin{aligned} \cosh (-l) \sqrt{yz} &= \cosh \sqrt{(y)(z)} \\ &= \cosh \sqrt{YZ} \end{aligned} \quad (3.49)$$

$$\begin{aligned} \text{and } \sinh (-l) \sqrt{yz} &= -\sinh \sqrt{(y)(z)} \\ &= -\sinh \sqrt{YZ} \end{aligned} \quad (3.50)$$

$$\begin{aligned} \text{So } I_R &= E_S \sqrt{\frac{y(-l)}{z(-l)}} \sinh (-l) \sqrt{yz} \\ &\quad + I_S \cosh (-l) \sqrt{yz} \end{aligned} \quad (3.51)$$

$$\text{or } I_R = I_S \cosh \sqrt{YZ} - E_S \sqrt{\frac{Y}{Z}} \sinh \sqrt{YZ} \quad (3.52)$$

$$\text{Similarly } E_R = E_S \cosh \sqrt{YZ} - I_S \sqrt{\frac{Z}{Y}} \sinh \sqrt{YZ} \quad (3.53)$$

Auxiliary Line Constants or Derived Constants. The eqn.(3.46) and (3.48) give the sending end voltage and current in terms of the receiving end voltage and current and line constants. These questions can be further simplified as :

$$\text{If } A = \cosh \sqrt{YZ} \quad (3.54)$$

$$B = \sqrt{Z/Y} \sinh \sqrt{YZ} \quad (3.55)$$

$$C = \sqrt{Y/Z} \sinh \sqrt{YZ} \quad (3.56)$$

The eqns. (3.46) and (3.48) can be written as :

$$I_S = CE_R + AI_R \quad (3.57)$$

$$E_S = AE_R + BI_R \quad (3.58)$$

$$\text{If } D = A$$

So, the eqn. (3.57) can also be represented as,

$$I_S = CE_R + DI_R \quad (3.59)$$

The constants A, B and C given by equations (3.56), (3.57) and (3.58) are called as Auxillary Constants or Derived Constants. It will be of interest to note that A and D are vector numeric quantities, while B has dimension of ohm and C has the dimensions of mhos,

The auxillary constants A, B, C, D in the equations of transmission voltages can be determined by the following three different methods :

1. By use of Hyperbolic charts
2. By use of Convergent series of Complex angle
3. By use of Convergent series of real values.

APPROACH TO FIND THE VALUES OF A1, A2, A3, A4 AND B1, B2,

B3, B4 :

$$\begin{bmatrix} A_o & B_o \\ C_o & D_o \end{bmatrix} = \begin{bmatrix} 1 & -j X_c \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A & B \\ C & D \end{bmatrix}$$

$$= \begin{bmatrix} (A - j X_C \cdot C) & (B - j X_C D) \\ C & D \end{bmatrix}$$

$$A_0 = (A - j X_C \cdot C) = (A_1 + A_3 X_C) + j(A_2 + A_4 X_C)$$

$$B_0 = (B - j X_C \cdot C) = (B_1 + B_3 X_C) + j(B_2 + B_4 X_C)$$

$$A = a_1 + j a_2 \quad B = b_1 + j b_2$$

$$C = c_1 + j c_2 \quad D = d_1 + j d_2$$

$$(A - j X_C \cdot C) = [(a_1 + j a_2) - j X_C (c_1 + j c_2)]$$

$$= (a_1 + j a_2 - j X_C \cdot C_1 + X_C \cdot C_2)$$

$$= (A_1 + X_C A_3) + j (A_2 + A_4 X_C)$$

$$A_1 = a_1 \quad ; \quad A_3 = C_2$$

$$A_2 = a_2 \quad ; \quad A_4 = -C_1$$

Similarly we can also obtain the values of B_1, B_2, B_3, B_4 .

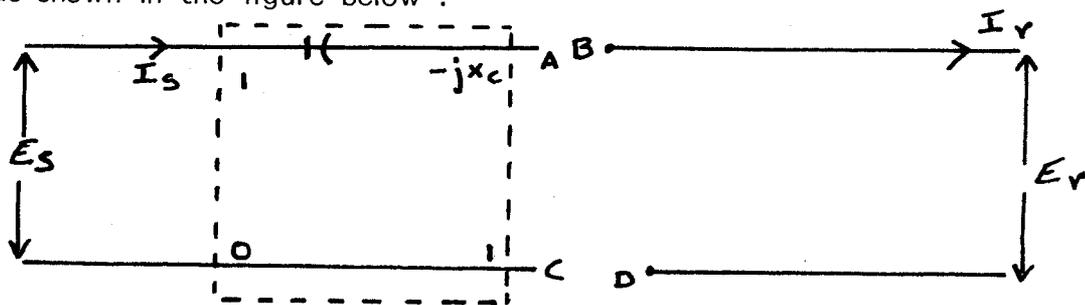
OPTIMUM COMPENSATION BY NEW METHOD

Transmission line inductive reactance has an important influence on power transfer. Reduction of this reactance can be best achieved by series capacitors.

This chapter brings out the straightway simple analytical method to find the value of X_c without resorting to the solution of polynomial equation and the inspection of roots.

LOCATION OF CAPACITOR

Considering the location of the capacitor at the sending end as shown in the figure below :



LINE PARTICULARS

The particulars of the following transmission line are considered

| | | |
|-------------|---|---------------|
| $E_s = E_r$ | = | 330 Kv |
| line length | = | 600 KM |
| Resistance | = | 0.0512 ohm/KM |

$$\begin{aligned} \text{Reactance} &= 0.512 \text{ ohm/KM} \\ \text{Shunt admittance} &= 3.33 \times 10^{-6} \text{ mho/KM} \end{aligned}$$

$$\text{Components of } A_0 = A_1 A_2 A_3 A_4$$

$$\text{Components of } B_0 = B_1 B_2 B_3 B_4$$

Coefficient values,

$$\begin{aligned} A_1 &= 0.7087 & B_1 &= 24.71 \\ A_2 &= 0.0275 & B_2 &= 276.99 \\ A_3 &= 0.00180 & B_3 &= 0.0275 \\ A_4 &= 0.0000192 & B_4 &= 0.7087 \end{aligned}$$

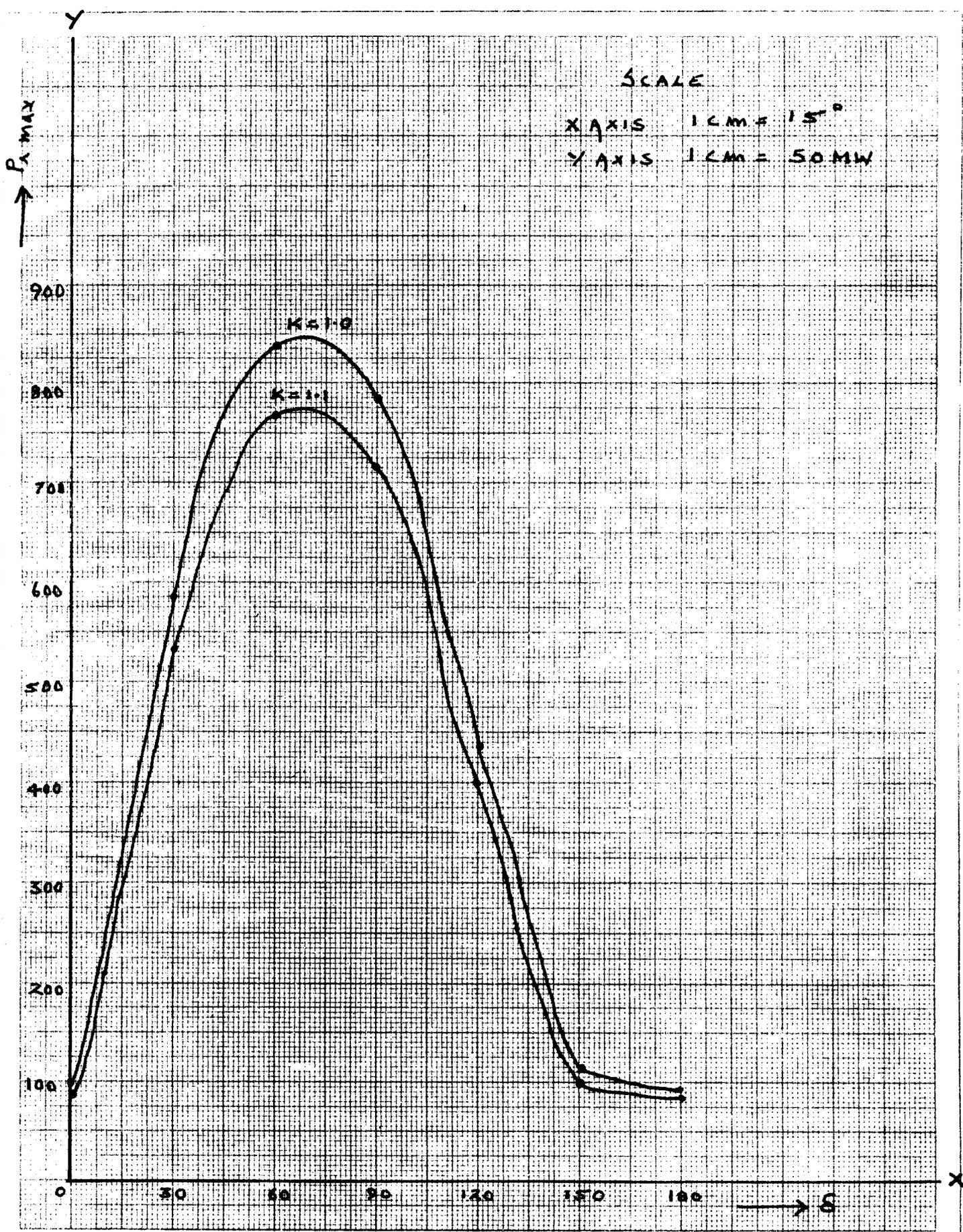
we know that

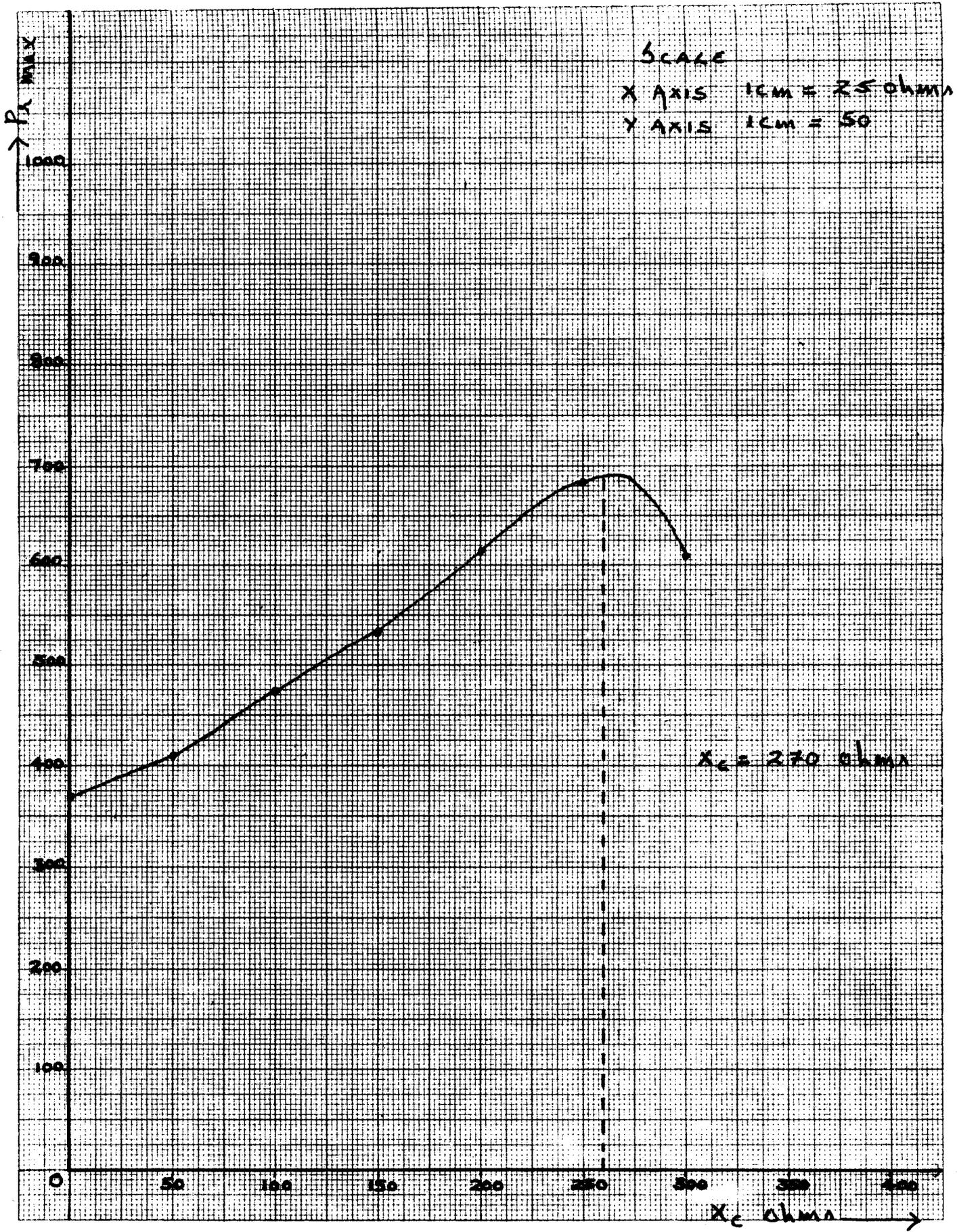
$$X_c = \frac{B_2 B_4 K + B_2 B_1 A_3 + B_2 B_3 A_1 - 2B_4 B_1 A_1}{B_4 B_1 A_3 + B_4 B_3 A_1 - 2B_2 B_3 A_3 - B_4^2 K} \quad (1)$$

The flow chart for the above equation is given in figure.

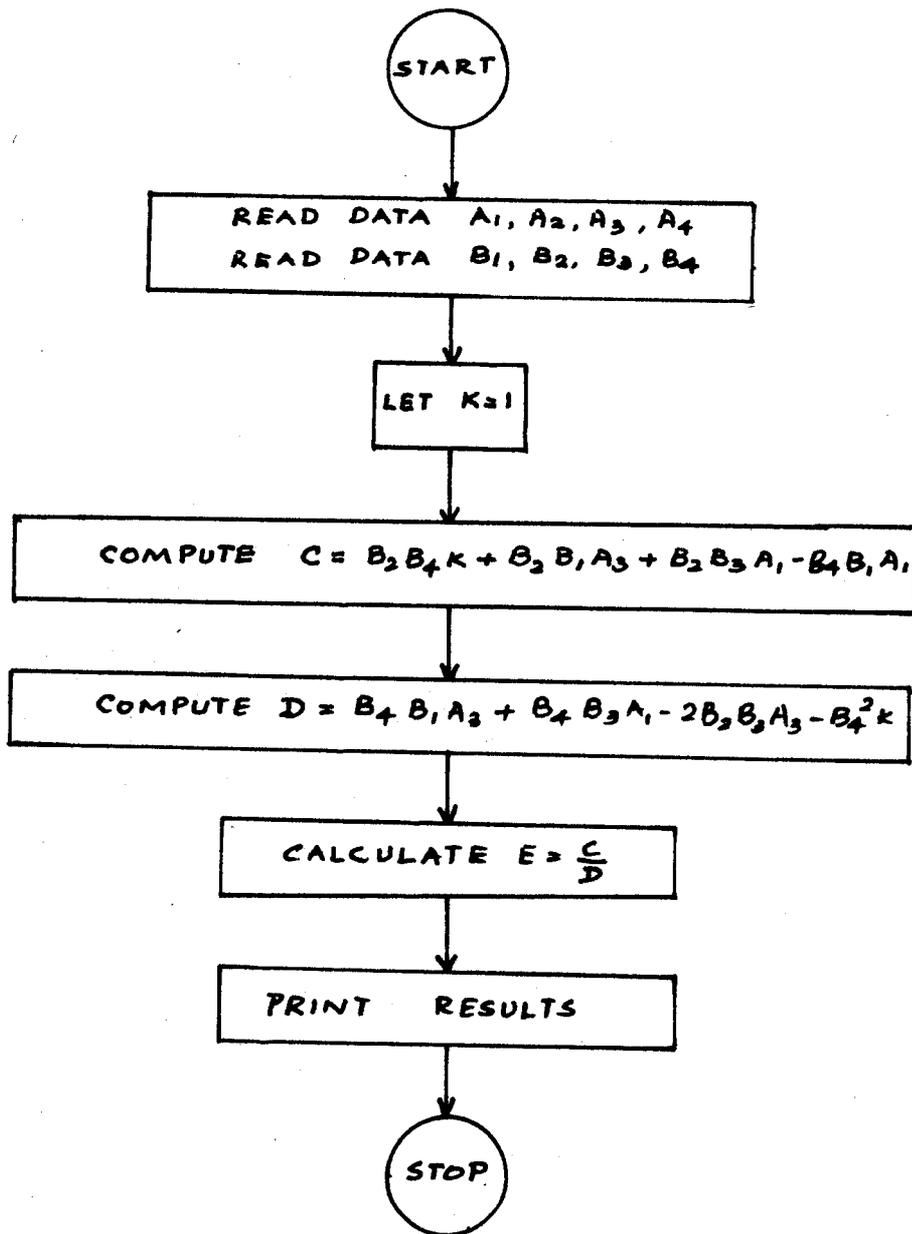
Based on the basic programme computer printout to the equation 1 is carried out and the value of X_c is 267.41 ohms. The same has been verified with graphical solution and the value of X_c is 240 ohms.

For the above compensation value, the power recieved at the receiving end is calculated varying the power angle from 0° to 180° in steps of 30 for $K = 1.0$ and $K = 1.1$ and is shown in the graph.





FLOW CHART FOR FINDING X_c :



```

CLS
GOSUB 60
XC = (B2 * B4 * K + B2 * B1 * A3 + B2 * B3 * A1 - 2 * B4 * A1 * B1)
XC = XC / (B4 * B1 * A3 + B4 * B3 * A1 - 2 * B2 * B3 * A3 - B4 ^ 2)
LOCATE 24, 20: PRINT "THE VALUE OF XC IS =", XC
END
60
LOCATE 6, 20: INPUT "ENTER THE VALUE OF A1.....", A1
LOCATE 8, 20: INPUT "ENTER THE VALUE OF A2.....", A2
LOCATE 10, 20: INPUT "ENTER THE VALUE OF A3.....", A3
LOCATE 12, 20: INPUT "ENTER THE VALUE OF A4.....", A4
LOCATE 14, 20: INPUT "ENTER THE VALUE OF B1.....", B1
LOCATE 16, 20: INPUT "ENTER THE VALUE OF B2.....", B2
LOCATE 18, 20: INPUT "ENTER THE VALUE OF B3.....", B3
LOCATE 20, 20: INPUT "ENTER THE VALUE OF B4.....", B4
LOCATE 22, 20: INPUT "ENTER THE VALUE OF K.....", K
RETURN
'DATA
'A1=.7087:A2=.0275:A3=.00180:A4=.0000192
'B1=24.71:B2=276.99:B3=.0275:B4=-.7087:K=1.0:

```

```

ENTER THE VALUE OF A1.....0.7087
ENTER THE VALUE OF A2.....0.0275
ENTER THE VALUE OF A3.....0.00180
ENTER THE VALUE OF A4.....0.0000192
ENTER THE VALUE OF B1.....24.71
ENTER THE VALUE OF B2.....276.99
ENTER THE VALUE OF B3.....0.0275
ENTER THE VALUE OF B4.....-0.7087
ENTER THE VALUE OF K.....1.0
THE VALUE OF XC IS = 267.4088

```

CHAPTER 4

HVAC - HVDC LINKS

HIGH VOLTAGE D.C INTERTIES

In India, 400 KV ac has been selected as the line voltage for interconnecting various regional grids.

For better operation of all thermal, hydro, nuclear power plants, they must be interconnected by HV lines. Two choices are before the system planners to select.

1. HVAC
2. HVDC

Possibilities of using HVDC links to interconnect the regional power grids depends upon the converter design technology. Cost of DC transmission line is less than cost of AC transmission line ; whereas cost of conversion equipment (converter and inverter) of dc is more than AC. If fall of cost of conversion equipment and rise in cost of AC transmission line the breakeven point is reaching fast when the total cost of HVDC system will become competitive to HVAC system.

NEED OF HVDC INTERCONNECTION LINKS :

INDEPENDENCE :

Connected AC systems remain completely with the own frequency and phase regulation.

Energy Flow :

Any preestablished schedule for the energy exchange will be strictly followed by DC interconnector.

STABILITY :

The DC links improve overall system stability.

FAULT CONDITION :

The DC link does not transmit AC power. Fault clearing in AC system is not aggregated. AC system fault conditions are not exported to other system.

LIMITATION OF HVDC LINKS

OVERLOAD CAPACITY :

Overload capacity can be obtained by oversizing the thyristors.

HARMONIC DISTORTION :

Harmonics are present in AC and DC sides.

DESIGN CONSIDERATION OF HVDC LINKS

Conversion equipment are very sensitive to temperature and hence atmospheric conditions play a very sensitive role in design. The existing lines will be a guiding factor in rule selection of HVDC lines.

OPERATING VOLTAGE :

The conversion equipment cost increases slightly with increase in voltage whereas the line cost reaches a minimum. Cost of transmission line is less ; But cost of conversion equipment are high and a transmission of ± 400 KV may be suitable for a power level of above 1500 MW.

ICE AND WIND LOAD:

Under strong wind, DC over voltage can exceed line insulation strength due to deflection on insulator string and reduction of the clearance to the structure. Contamination of insulator surface in coastal areas when the salt is blown in land from the sea during storms may pose a serious problem. When the insulators are wetted by fog, snow or light rain a leakage current will increase. Salt deposition on the insulators under the worst 'Salt' storms decide the number of the insulators.

TRANSMISSION LINE CONDUCTORS :

If wind velocity is high or salt contamination is high a single conductor is suggested. A bundle conductor results in more deposition of salt and more tension. Near coast, the salt deposition is high and hence 'V' string instead of 'I' string is preferred as 'V' string has better washing performance than 'I' string. The conductor diameter must be large enough to avoid corona. Maximum conductor temperature under normal and peak load condition must be less than 90°C . As the thermal effects are apparent on the annealing of the conductor above this temperature.

COST ANALYSIS :

A large part of the cost is incurred on the conversion equipments and the cooling process. Forced air, water or oil cooling of the static equipment is used. Though air as the cooling medium is the cheapest it involves more cost for the civil work like building etc. Water is cheaper to oil but it requires more equipments to process it before it reaches the semiconductors. Oil requires less cooling space, but it is cost-lier than the other.

RELIABILITY:

Overall reliability of HVDC line is the reliable operation of transmission line and convertor equipments.

TRANSMISSION LINE :

It is expected that a bipole transmission line outages every fifty years and hence twice reliability of three phase line. In case of failure of one pole, other pole may takeover the load.

CONVERSION EQUIPMENTS :

The reliability of thyristors and conversion equipments have been absorved to be about 95%. If stringent measures are taken to follow the schedule of operation, with the development of light sensitive gates, the thyristors can now be fixed simultaneously ensuring more reliable fixing.

ADDITION OF A DC LINK IN PARELLEL WITH AC TYPE

METHODS TO INCREASE POWER TRANSFER :

The transmission of bulk power between two AC system is being done mostly using HV or EHV AC transion line. The lines may already have series capacitors compensating a part of line reactance; and it is assumed that further compensation to increase the steady state stability limit is not feasible, because further increase of power transfer between two systems can be achieved by one of the following methods:-

- a. Planning the lines for future power increase at the time of initial commisioning.
- b. Increasing the voltage level of AC lines.
- c. Conversion of existing AC lines into DC transmission lines.
- d. Comisioning additional AC transmission lines.
- e. Commissioning of d.c link in parellel with existing AC lines.

METHOD (a) :

This is a practice commonly followed for lines constructed on a new route. The transmission system, though designed for ultimate ratings is initially comisioned for a small power transfer. Later and planned increased of powertransfer can be achieved in a variety of ways, two of which are discussed below :

1. Transmission towers though built for double circuit operation are initially provided with only one circuit operated at the rated voltage. In such cases, the designed two fold power increase is achieved at a later stage. By adding the remaining three conductors on the tower and installing the other equipment in the substation for the second circuit.
2. The transmission towers and lines though designed for full voltage are operated in the initial stage of working at reduced voltage, usually 50%. In such cases a four fold increase of power capacity is achieved by increasing the voltage to the originally designed level at a later stage by minor replacements at the substation.

In the above two approaches, if properly planned the power interruption is likely to be small during commissioning work. However, in such cases when the power increase is desired on a route on which there exist one or more circuits of AC lines, already working at the rated voltage and power. One of the methods described in the following sections becomes necessary.

METHOD (b)

INCREASING THE VOLTAGE LEVEL OF AC LINES :

For AC transmission lines commissioned two or three decades ago based on very pessimistic designs, increase of voltage level can be achieved by minor modifications of the transmission line structures.

Replacement of conductors and replacement/addition of components at the terminal substations.

Another technique recently considered is the conversion of the double circuit existing AC lines to single circuit AC lines of higher voltage by minor modification of tower structure and substations.

In the above cases, it is necessary to plan ahead as to how the system can be converted with as little power interruption as possible while these circuits are deenergised . Also if these are cables existing on some section of the transmission system through river or thickly populated areas, the feasibility of using higher voltage AC cables has to be studied carefully, this is so because for the same distance enormous charging current for higher voltage ac cables may necessitate its compensation by the installation of shunt reactors.

In optimally designed EHV systems the uprating may not always be economical.

METHOD (c) :

Existing three phase double circuit overhead transmission lines can be converted into three circuits of bipolar DC transmission systems. The transmission line components could be used without much modifications, but the substations at sending end and receiving end have to be modified substantially to work on the DC system.

Though this method is technically feasible, literature have not reported enough evidence in support of this alternative possibility

because the increase of power transfer is very small and the cost of conversion may not be justifiable.

METHOD (d) :

Mostly used for increasing power transmission on a given route. i.e, increase of parallel circuits means a reduction of the system impedance and hence increase in the existing short circuit level, which may exceed the capacity of the existing circuit breakers or cause unacceptably high electrical and mechanical stresses on the system equipment.

The transfer of large power over A.C. interties between two A.C. systems pose problems of dynamic instability in the network and the sustained oscillations of low frequency are not controllable even by the power system stabilizers in the excitation systems of generators. This may impose constraint on the amount of power that can be transmitted over the interties.

METHOD (e) :

This approach consists of commissioning bipolar double circuit lines in parallel with the existing A.C. Lines to achieve the desired increase of power transfer as compared with other approaches. The parallel D.C. link gives the following advantages :

- a. D.C.Link offers the increase of power transfer without increase of short circuit level at the point of connection to A.C. system.

- b. There is very little interruption of power transmission between the two systems during commissioning of new D.C.Link.
- c. The converters have the property of being able to generate D.C. Voltage of any polarity within a set of voltage levels. By adjusting the polarity of D.C.Voltages at the two ends of the transmission line, a current can be made to flow, the magnitude of which is determined by the voltage difference of the two converters and the resistance of the line. Thus the desired steady state power transfer between the two A.C.Systems can be achieved using the new D.C.Link.
- d. The converters have the capability to switch current instantaneously by simple control action. Thus changing, "reversing or stopping" of power flow in the D.C.Link by the action of control on converters can be used for controlling also the abnormal developments in the D.C. & A.C. Systems.
- e. For A.C. - D.C. Lines running on the same towers, a lightning has often hit both the circuits simultaneously thus giving a complete interruption of the power transfer. For D.C.system, lightning has never known to hit there could be half the power transfer even in case of lightning.
- f. D.C. system can be commissioned with any desired power rating irrespective of the rating of the interconnected

system. That means, the interconnection by D.C. can be started with some few percent of the ultimate power capacity and can be later extended in stages as per the plan. This flexibility of D.C. Link is a great advantage to planning and operating engineers.

- g. With the rapid advantages in the converter technology the costs have come down substantially and the performance of present HVDC schemes confirm that HVDC technology has reached the stage where it can be applied with the same degree of confidence as the AC power transmission because for the same distance and power transmitted, a new DC link may be preferred over a new AC line.

DESIGN ASPECTS OF D.C.LINK IN PARALLEL WITH A.C.LINES

If a single circuit D.C.link of rating comparable to the existing AC lines is added between two AC systems sudden and sustained interruption to the power flow on the DC link may result in a loss of synchronisation between the two AC systems. Because parallel operation of single circuit monopolar DC link and or more AC lines is inadvisable unless the AC lines are strong enough to withstand the permanent loss of the DC link.

However, if there are two or more DC circuits in parallel with one or more AC lines the DC systems can be so arranged that if one of the DC circuits is lost, the other DC lines takes the increased

load by increase of direct current. In this case, there is no serious stability

Therefore for operational purposes, each poles of bipolar DC lines is considered as a separate circuit with earth return.

In both the monopolar and bipolar systems, for a temporary earth fault in DC line, the concerned converters could be blocked for a few cycles and then operation on the recovered line may be resumed in a very short time. The effect of a temporary earth fault in DC line on the AC system is very small compared with the case of a three phase fault on the AC lines, and that this fault does not have much significant effect of the transient stability of the two AC systems.

SHUNT CAPACITANCE OF AC LINES AND REACTIVE POWER REQUIREMENTS OF CONVERTERS :

The EHV AC Transmission line is characterised by its series reactance and shunt capacitance. The series reactance absorbs reactive power, the shunt capacitance affect results in generation of reactive power.

At surge impedance loading, the reactive power generation and absorption are equal. Below the surge impedance loading the shunt capacitance effect predominates and requires that the reactive power generated by the AC transmission lines be absorbed by the AC system connected to the two terminals lines. For EHV AC transmission lines, the reactive power generated at no load may be of the order of 0.4 to 0.5 MVAR / mile for a 275 Kv line and 1 to 1.1 MVAR/mile for a

400 Kv line.

For a DC link on the other hand, the operation of converters requires the supply of reactive power from AC terminals and therefore DC schemes are always equipped with either synchronous condensers or suitable banks of static capacitors. The requirement of reactive power increase with the power transmitted by DC link and may be of the order of 0.5 to 0.7 MVAR / M.W. of the power transmitted.

Therefore, when the DC link is commissioned in parallel with the AC transmission lines it is natural that the advantage be taken of the above situation. For example, during light loads on the AC lines the power flow in the DC link and the operation of the synchronous condensers or static capacitors could be so controlled that the reactive power generated by the AC transmission lines is absorbed as much as possible by the converters of the DC link, this will avoid the generators in the power systems from getting strained to absorb the reactive power of the AC lines.

However, it should be not understood that the AC lines could supply the reactive power requirements of the converters and the synchronous condensers or static capacitors could be dispensed with. This is so because, when the AC lines carry their rated load, they can hardly supply any reactive power.

CONTROL OF DC POWER IN CASE OF AC LINE FAULT :

Consider one or two DC - AC lines and a parallel DC link supplying power from system 1 to 2. In case of fault on one of the

AC lines, power transmitted over the AC lines will get reduced substantially and the power transmitted over the DC link will drop inspite the converted controls. Thus the power output from system will be less than the mechanical power inputs to generators and it will experience acceleration. For system 2 the power input will become less than the loads and the machines will experience retardation. This will result in the increase of phase angle between the sending end receiving end voltage of the transmission (AC) lines between the systems 1 And 2. Therefore attempt should be made to keep the DC line power, during period of the AC line fault, to so near its maximum value as possible so that the acceleration of system and the retardation of system 2 are minimum giving seperation between the phase angles of sending end and receiving end voltages of the AC interties.

After clearance of fault, on the line by opening of the corresponding circuit breakers the number of parallel AC transmission circuits between the Two AC systems will reduce and the power angle curve for the power transmitted over the AC lines will be lower than that before the fault. However, the increased angle between sending end and receiving end voltages will give power transfer from system 1 to 2 higher than that existed before the fault. Therefore system 1 will experience retardation and system 2 will have acceleration. At this stage also, the control of DC link should be desinged to temporarily increase the DC power, so that the decelerating power acting on system 2 are large. This enables the internal angles of the two systems to return quickly to new steady values before they cross the transient **stability** limits.

With the above discussion it can be said that higher the ratio of DC power to the total power transmitted from system 1 to system 2 during the station operation lesser will be the effect felt by the two AC systems of the power reduction during the AC line fault and therefore higher will be the transient power limit. Further power in the DC link should be increased by increase of the direct current as soon as AC line fault is detected. For this the drop in AC terminal voltage of the converter could be taken as the signal to increase the margin angle of inverter for getting the desired current increase.

Though in almost all cases DC link commissioned in parallel with existing AC lines will improve system performance, yet in many cases the improvement will be less than that could be obtained with new AC line instead of DC line. This is because, the new AC line will increase the synchronizing power in the system after the fault clearance while the DC link makes no contribution in this respect. Thus in many cases, the stability limit calculated may be higher with new AC lines instead of DC link.

CONTROL OF CONVERTERS TO DAMP AC SYSTEM OSCILLATIONS

In AC systems, automatic voltage regulator and governors provide means of damping oscillations and prevent dynamic instability. When a DC link is also present in the system, the appropriate utilization of fast controllability of the power flow in the DC link can significantly damp the oscillation in the associated AC network.

The power flow in the DC link is modulated by the reference current control of the convertors which are working in the constant current mode. For this, a suitable signal from the AC system is taken and fed through appropriate filters, transducers and compensating circuit to the reference circuit of the converter current regulator. However, owing to the nature of the DC link operation the effect on the overall system of control of the reference current depends significantly on the system operating condition and parameters. In fact a DC link references current control system which improves stability at one operating point may have a detrimental effect at other system operating conditions. Therefore, a predictive or adoptive types of current regulator circuits would be needed to improve the system stability for a wide range of system operation.

The modulation of direct current line could be based on a suitable signal from the AC system. The use of frequency difference between the two interconnected AC system is a commonly used approach. However, for long distance HVDC transmission system the use of frequency differences as the modulating signals will pose serious problems.

The major problem in the use of frequency difference as the modulation signal will be needed for telemetry of frequency signal from the inverter terminals over a communication channel of considerable length to the rectifier terminals, posing problems of reliability and equipment coordination between the two different AC systems.

An alternative signal could be to use rate of change of AC iterative power as the modulation signal for DC interties. For constant voltage $V_1 \angle \delta_1$ and $V_2 \angle \delta_2$ at sending end and receiving end respectively. The power in the AC intertie is

$$P_{ac} = (V_1 V_2 / X) \sin (\delta_1 - \delta_2) \quad (1)$$

where X - Reactance of AC circuit. For small perturbations the change of intertie power is

$$\Delta P_{ac} = (V_1 V_2 / X) \cos (\delta_1 - \delta_2) (\Delta \delta_1 - \Delta \delta_2) \quad (2)$$

The time derivative of this expression gives

$$\frac{d P_{ac}}{dt} = (V_1 V_2 / X) \cos (\delta_1 - \delta_2) \left(\frac{d \delta_1}{dt} - \frac{d \delta_2}{dt} \right) \quad (3)$$

This equation shows that the rate of AC intertie power also yields the frequency, difference information, as indicated by the last factored expression but now with only a signal measurement of rate of change of power made at sending end. This approach has been successfully employed to prevent damping of low level oscillation of the AC interties by modulation of Direct Current by $\pm 3\%$. The DC modulation is a very effective means of providing system damping without degrading the operation of the DC line and that even a small modulation signal can provide sufficient damping for disturbances in AC systems. The successful operation of DC modulation was a key factor in permitting an increase of rating AC interties.

However, near the steady state stability, changes in AC power transmission are insensitive to change in the reactive angle between the systems and as a result, the time derivative of AC power is not a good indicator of the frequency difference.

Another possible approach could be to use the rate of change of AC inertias current as the signal for the modulation. The AC inertias current like AC power can be obtained by a signal measurement but unlike AC power a strongly related to the relative angle between the system even at the steady stability limit. Therefore these are plans to develop a current based modulation system for the inertias.

CHAPTER 5
OVER VOLTAGES IN HVAC TRANSMISSION AND
HVDC TRANSMISSION SYSTEM

The various type of the over voltage which can stress the insulation in EHV system can be classified as

1. External over voltages due to lightning
2. Internal over voltages due to switching.

The two important switching operations which cause severe over voltages in EHV systems are

- a. Line energization
- b. Load rejection at the load end of the line.

External over voltages are basically the atmospheric over voltages caused by lightning phenomenon and are less important in 400 KW system. It is well recognised that only direct lightning strokes constitute a risk of failure on EHV systems. It is very important to assess the magnitude of such voltages. Because it is natural and random phenomenon. The lightning arrester is a standard device for protection against lightning.

The internal over voltages are caused when the system operating conditions are changed from one to another. These over voltages are of different nature and therefore they stress the insulation in different form. These over voltage can be classified as follows based on their characteristics.

1. Switching over voltage
2. Dynamic over voltage
3. Steady state over voltage

SWITCHING SURGE OVER VOLTAGE : These over voltage are basically transient over voltages and are caused by energisation and re-energisation of transmission lines. They can also be caused by the initiation of faults, but the magnitude of these faults surges is not very high and therefore they are not considered in 400 KV systems. Their over voltages are very high when an open ended line is re-energised rapidly. The use of permanently connected shunt reactors and use of circuit breakers choosing resistors are well known and have been universally tried.

DYNAMIC OVER VOLTAGES :

These over voltages are transitional between transient and substation network operating conditions. Basically these are power frequency over voltages and are characterised by slow voltage variations contained in an envelope. They can last as long as one second and the effect of such over voltages is more when they are accompanied by single line to ground fault. These over voltages are dependent on the following parameters.

- Source parameters
- Line parameters
- Network configuration
- Automatic voltage regulator action
- Governor action.

These over voltage can reach as high as 2.5 to 3.0 p.u. If ferro resonance takes place due to low side switching of inter connecting transformers. These over voltages can be controlled by the use of shunt reactors permanently connected with the line.

Steady State Overvoltages : It can take place in long open ended lines due to Ferranti rise. This situation may exist for a few minutes while line charging these overvoltages can be controlled by using permanently connected shunt reaches. Long transformer connected lines sometimes cause Ferro resonance because of line capacitance and transformer magnetising reactance. This may cause over voltage of the order of 2.0 pu. under steady state and must be avoided.

MATHEMATICAL ANALYSIS AND SOLUTION OF TRANSMISSION LINE

TRANSIENTS :

With the increasing trend towards EHV transmission voltage of 400 KV, the study of transient phenomenon in transmission lines has become extremely important. The basic insulation level nowadays for a EHV transmission is determined more by the behaviour of the switching and fault conditions than by its behaviour to lightning surges. The precise calculation of these over voltages at the design stage will help in taking necessary precautions to reduce these over voltages.

Owing to the rise in the system operating voltages the transient over voltage is due circuit breaker closing is more important than transient over voltages due to circuit breaker opening. Consider a three phase transmission line composed of three individual conductors parallel

to the surface of the earth line energization of the line will be considered as sending end at which there will normally appear generation while the receiving end located at a distance X_0 km away will be considered the receiving end at which there will normally appear a load.

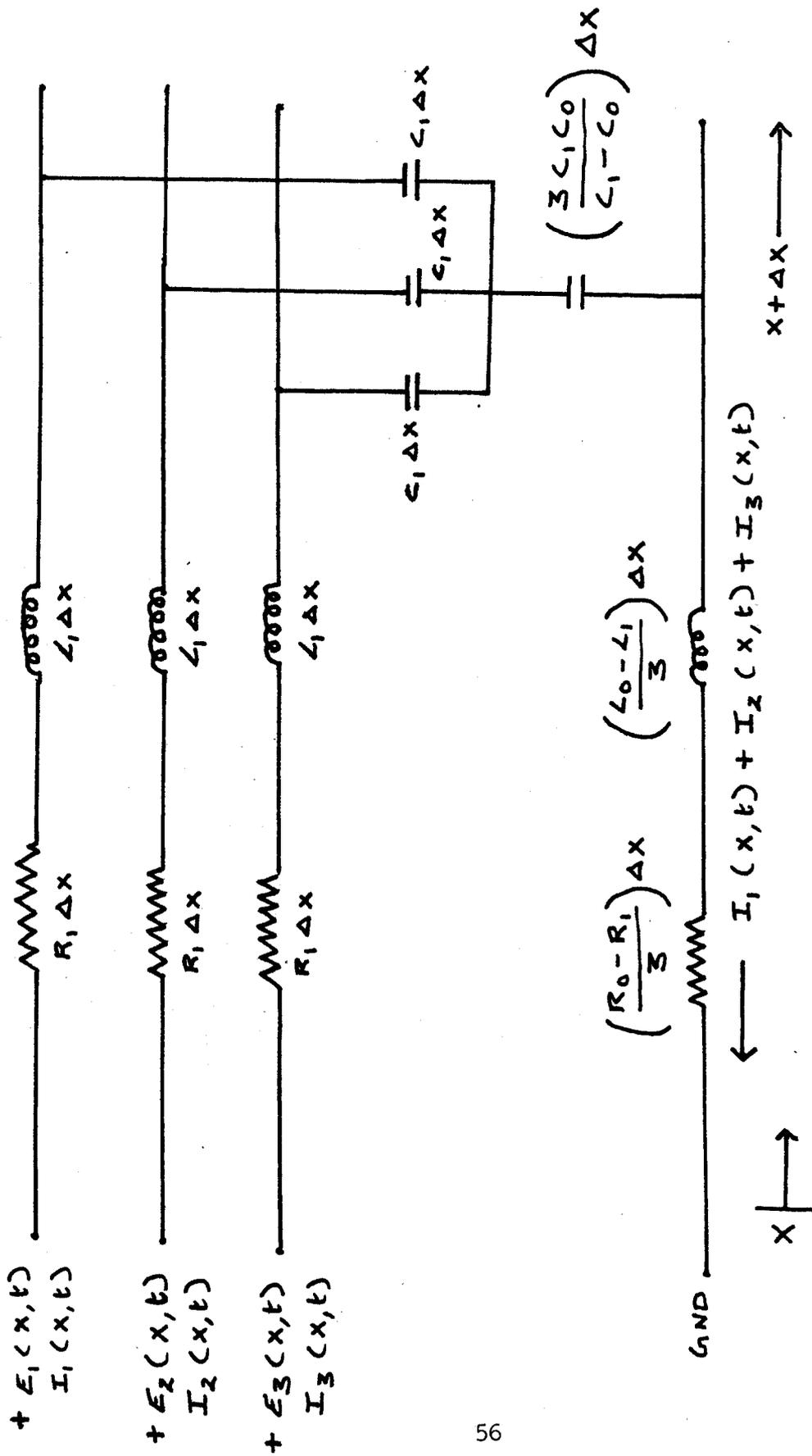
The quantities of interest in this system are the voltages with respect to ground at any point along the line and the currents in the conductor. Each of these are functions of two variables, position X along the line, measured from reference point and time ' t ', measured from across reference time primary emphasis will be placed on the voltages and currents at each end of the line at which the various terminations will present boundary conditions necessary for solving the system equations.

EQUIVALENT CIRCUIT FOR A THREE PHASE TRANSMISSION LINE:

In this circuit the over head conductors are described by the positive sequence parameters while the effects of the ground return are accounted for with zero sequence parameters.

A mathematical description of a transmission system is developed and the simultaneous partial differential equations are formed which further reduce to differential matrices. These matrix differential equations are solved through a transformation of coordinates which produces a general solution of the system voltages and currents.

Transformation of variable is made such that the actual transmission line voltage (E) are related linearly to a new set a variable



EQUIVALENT CIRCUIT FOR 3- ϕ TRANSMISSION LINE

(F). Then if the transformation is carefully chosen the matrix differential equation describing the system may be written as by supposing that the transformation made is related as

$$\begin{aligned} [E] &= [T] [F] \\ [F] &= [T]^{-1} [E] \end{aligned} \quad (1)$$

Where $[T]$ is numerically constant matrix.

In more compact forms to illustrate the three phase transmission line relationship it is written as

$$\frac{d^2}{dx^2} [F] - [T]^{-1} [\alpha] [T] [F] = 0 \quad (2)$$

$$\text{Let } [Z] = [T]^{-1} [\alpha] [T] \quad (3)$$

Equation (2) becomes

$$\frac{d^2}{dx^2} [F] - [Z] [F] = 0 \quad (4)$$

Now matrix $[Z]$ is the diagonal matrix then the voltage equations are expressed as

$$\frac{d^2 F_1(x,s)}{dx^2} - Z_{11} F_1(x,s) = 0 \quad (5)$$

$$\frac{d^2 F_2(x,s)}{dx^2} - Z_{22} F_2(x,s) = 0 \quad (6)$$

$$\frac{d^2 F_3(x,s)}{dx^2} - Z_{33} F_3(x,s) = 0 \quad (7)$$

Where Z_{11} , Z_{22} and Z_{33} are the elements of the diagonal matrix Z

$$Z = \begin{bmatrix} Z_0 Y_0 & 0 & 0 \\ 0 & Z_1 Y_1 & 0 \\ 0 & 0 & Z_1 Y_1 \end{bmatrix} \quad (8)$$

Hence equations (5), (6) and (7) are as follows :

$$\frac{d^2 F_1(x, s)}{dx^2} - (Z_0 Y_0) F_1(x, s) = 0$$

$$\frac{d^2 F_2(x, s)}{dx^2} - (Z_1 Y_1) F_2(x, s) = 0 \quad (9)$$

$$\frac{d^2 F_3(x, s)}{dx^2} - (Z_1 Y_1) F_3(x, s) = 0$$

Since coefficients $(Z_0 Y_0)$ and $(Z_1 Y_1)$ are not functions of x , equation (9) may be solved for transformed coordinates.

$$\begin{aligned} F_1(x, s) &= K_{11} e^{-\sqrt{Z_0 Y_0} x} + K_{12} e^{\sqrt{Z_0 Y_0} x} \\ F_2(x, s) &= K_{21} e^{-\sqrt{Z_1 Y_1} x} + K_{22} e^{\sqrt{Z_1 Y_1} x} \\ F_3(x, s) &= K_{31} e^{-\sqrt{Z_1 Y_1} x} + K_{32} e^{\sqrt{Z_1 Y_1} x} \end{aligned} \quad (10)$$

It is advantageous to write the solution in equation (10) in matrix form as follows :

$$[F] = [K_1 \cdot e^{-x}] + [K_2 \cdot e^{+x}] \quad (11)$$

Finally the solution of the actual line voltage may be expressed follows:

$$\begin{aligned} [E] &= [T] [F] \\ &= [T] [K_1 \cdot e^{-x}] + [T] [K_2 \cdot e^{+x}] \end{aligned} \quad (12)$$

PROCEDURE FOR FINDINGS OUT TRANSIENTS FOR SINGLE PHASE SYSTEMS :

Assuming the lines to be initially unexcited the differential equations relating the voltage and current in the transmission line can be written in the form, in Laplace domain as,

$$-\frac{dV}{dx} = (R + sL) \cdot I \quad (1)$$

$$-\frac{dI}{dx} = (G + sC) \cdot V \quad (2)$$

Where V and I are the transformed variables voltage and current with respect to time and R, L, G and C which are Resistance, Inductance, conductance and capacitance of the line per unit length respectively.

The solution of the equation (1) and (2) can be written as

$$V_s(t) = K_1(t) + K_2(t) \quad (3)$$

$$V_R(t) = A(t) + B(t) \quad (4)$$

$$i_s(t) = 1/Z K_1(t) - K_2(t) \quad (5)$$

$$i_R(t) = 1/Z A(t) - B(t) \quad (6)$$

With the assumption that the line conductance $G = 0$, it can be found that

$$A(t) = e^{-R/2 \sqrt{C/L} \cdot x_0} \cdot K_1(t - \sqrt{LC} \cdot x_0) \quad (7)$$

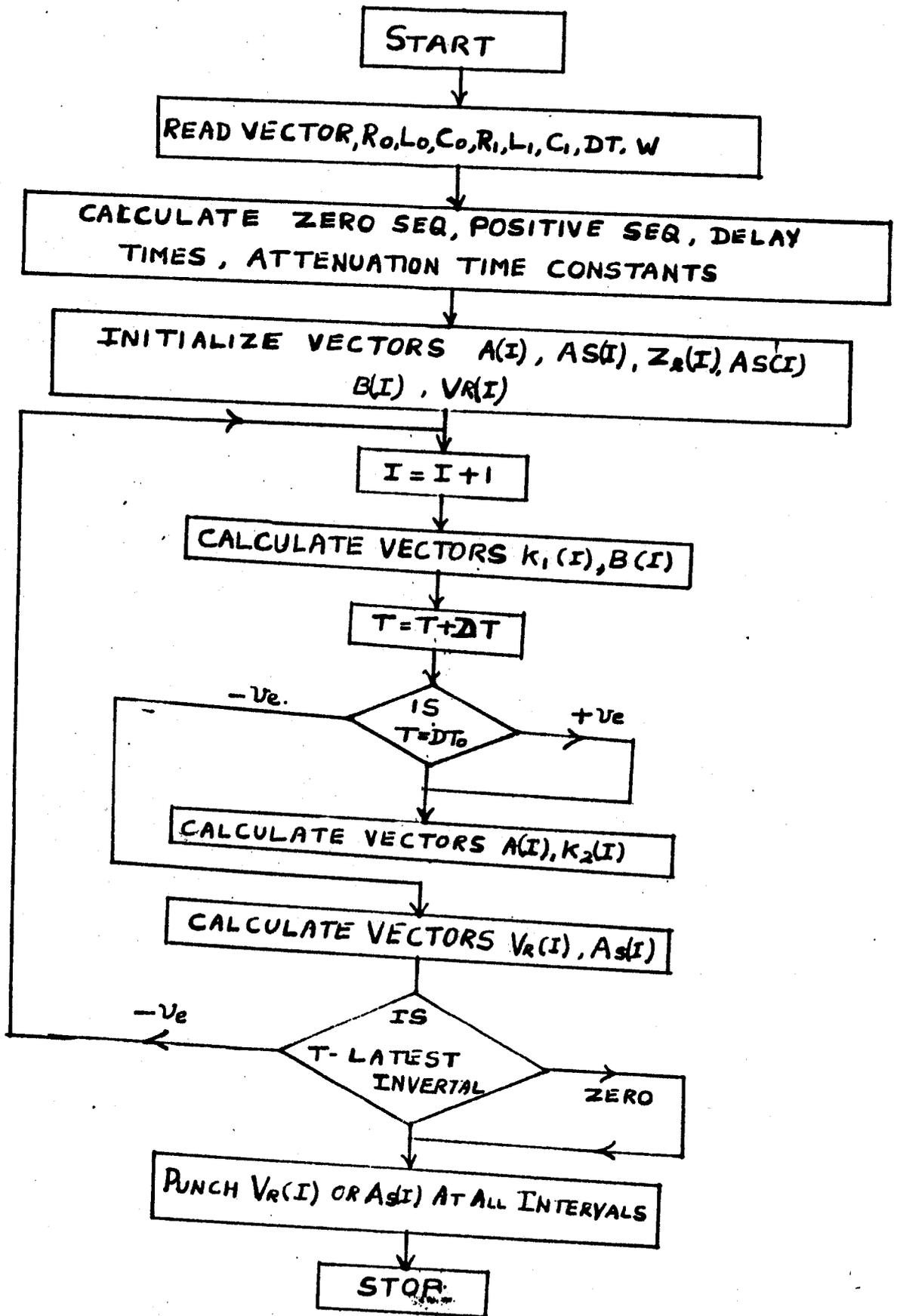
$$K_2(t) = e^{-R/2 \sqrt{C/L} \cdot x_0} \cdot B(t - \sqrt{LC} \cdot x_0) \quad (8)$$

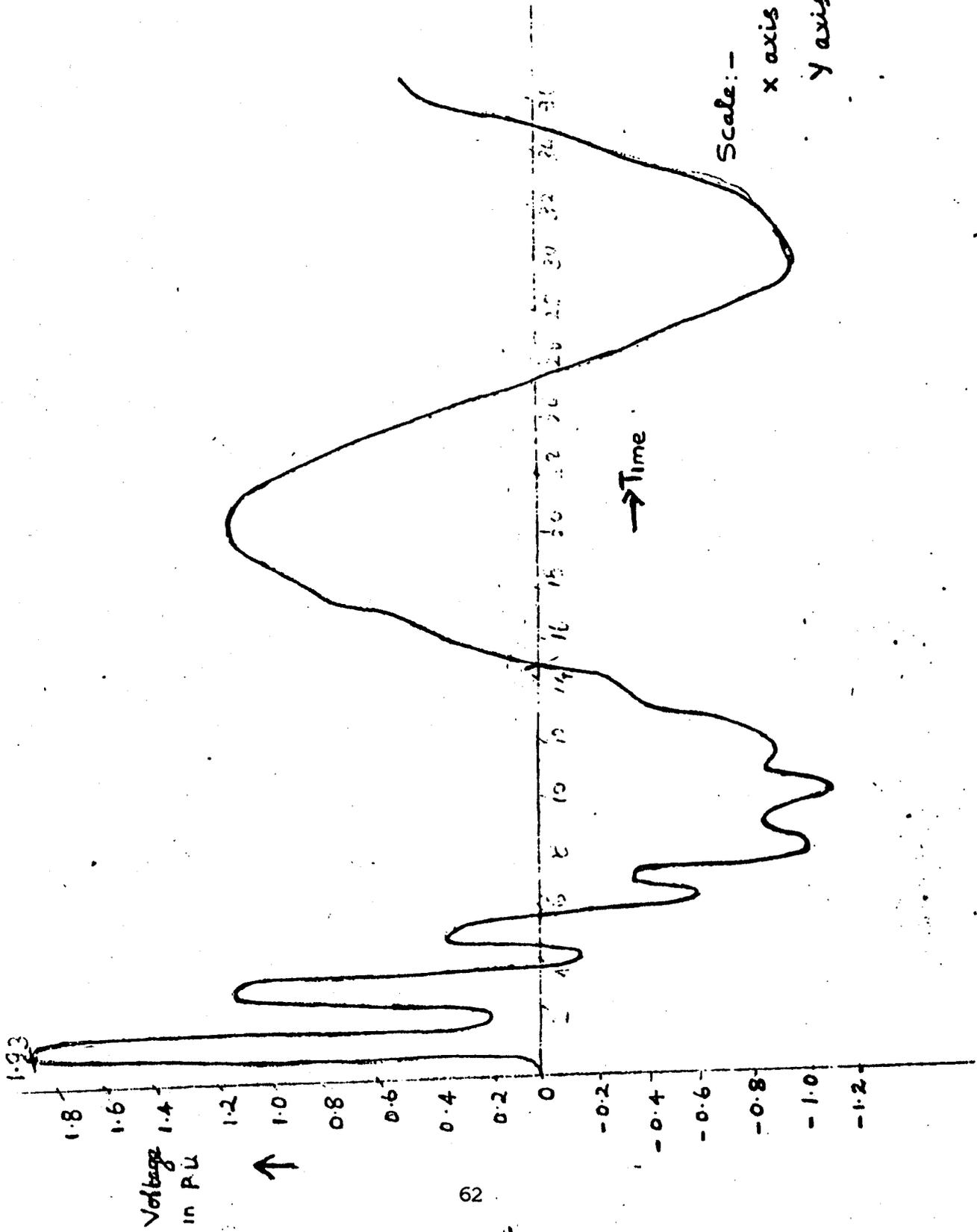
Where x_0 is the length of the line and $Z = \sqrt{L/C}$ ie, 'A' is a delay function of K_1 and K_2 is the delay function of B with an attenuation factor of $e^{-R/2 \sqrt{C/L} \cdot x_0}$.

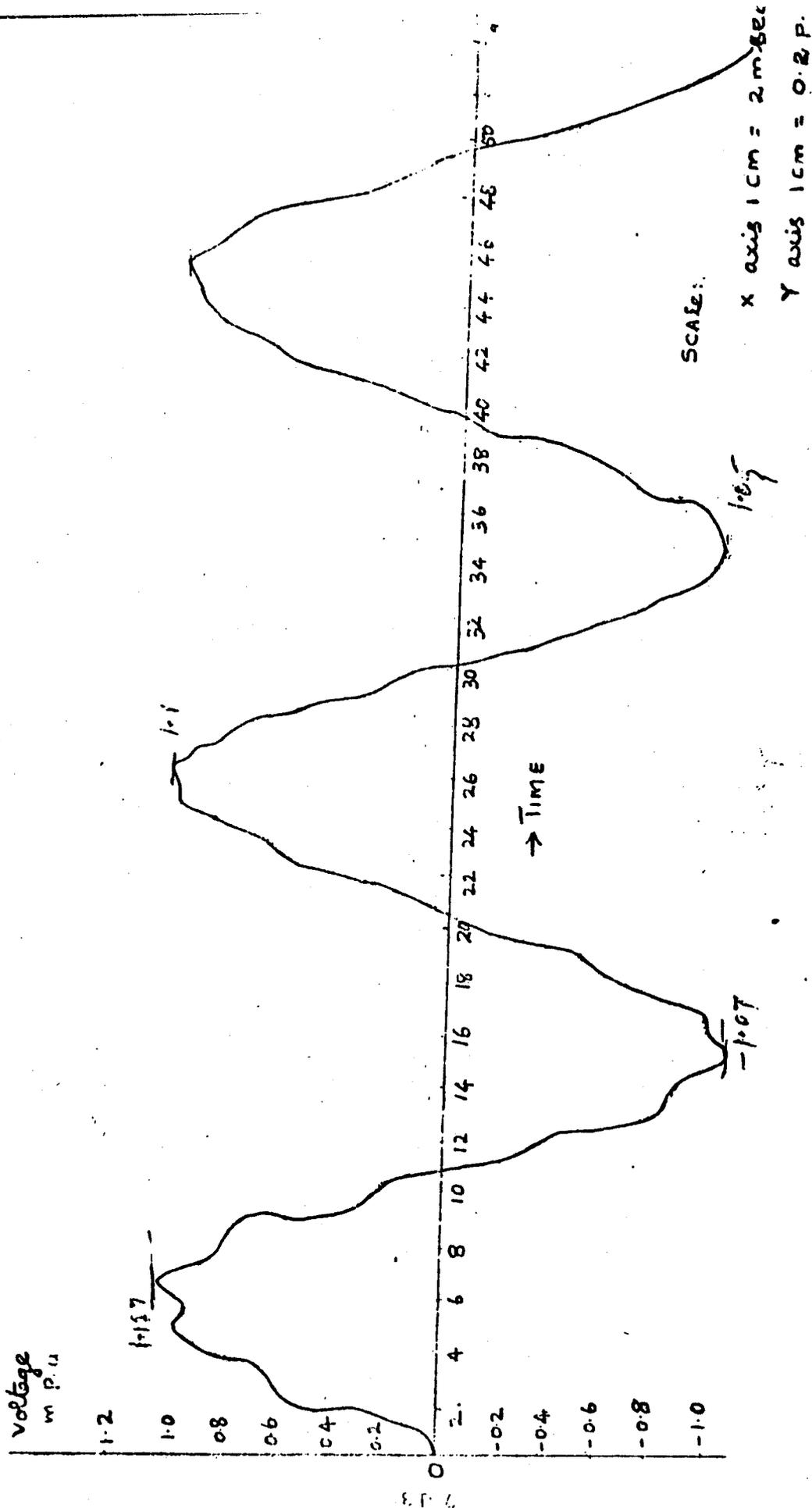
From equations (3) to (6) it can be observed that the receiving end voltage and current and the sending end voltage and current are expressed in terms in A, B, K_1 and K_2 .

Thus the solution of transient phenomena essentially involves the evaluation of the above four functions. As an example consider a line energization study involving the energization of a transmission line open circuited at the receiving end. The flow chart is shown in figure. The voltage at the receiving end at different times are plotted for a difference instant of closing of the source voltage.

FLOW CHART FOR CALCULATION OF EMV LINE TRANSIENT







OVERVOLTAGES IN A HVDC SYSTEM DUE TO LOAD REJECTION AT

INVERTER:

INTRODUCTION

A knowledge of the Overvoltage caused in a HVDC system due to change in load and load rejection in the system is important for proper coordination of the insulation as well as for the design of effective protection scheme. The insulation in the system is significantly influenced by the short duration and temporary overvoltages. A change in load or load rejection at an inverter in the system, which can be intentional or initiated due to system operational requirement can cause such Overvoltages. A novel convertor model which yields a modular analysis for a HVDC system has been used for the study of overvoltages.

Figure shows the equivalent circuit of a 6 pulse convertor during a commutating interval. Here i_{cir} is the circulating current and the net voltage driving this current is $e_{cir} = e_R - e_B$. Similar equivalent circuits for all the commutating intervals have been drawn and an examination of these circuits yield a general set of voltage and current equations (1) to (4) describing any commutating interval.

$$C_{cir} = a (e_i - e_k) = i_{cir} (Z_i + Z_k) - i_{dl} Z_k \quad (1)$$

$$V_{dl} = a (V_i - V_j) \quad (2)$$

where $V_i = e_i - i_i Z_i$; $V_j = e_j - i_j Z_j$

$$i_i = i_{dl} - i_{cir} \quad ; \quad i_m = i_{dl} \quad ; \quad i_{m+1} = i_{cir} \quad (3)$$

$$i_i = a i_{m+1} ; i_j = i_j = -a i_m ; i_k = a i_1 \quad (4)$$

The suffices i,j,k will assume one of the phase notations R, Y or B. Suffices 1, m and m + 1 will assume one of the numerals 1 to 6 and the multiplier a will be either +1 or -1.

With the knowledge of equations (1) to (4) corresponding to a particular commutating intervals, the equations describing the subsequent commutating intervals can be obtained by cyclically modifying the phase notations of the source voltage, currents and impedances in the order R Y B by cyclically incrementing the suffixed numerals (1,m,m+1) of the thyristor currents and by altering the sign of the multiplier a. These modifications are effected at every triggering of a thyristor.

THE MODEL OF THE HVDC SYSTEM :

The proposed converter model is utilised in the analysis of a HVDC Link (Fig. 2) and a 3 terminal HVDC system (Fig.3) where the various subsystems and components are represented as follows :-

- a. The AC system by a sinusoidal voltage behind the Thevenin's equivalent impedance as viewed from the converter busbars.
- b) The converter transformer by an ideal transformer in series with its leakage impedance.
- c. The DC line by its T/ equivalent network.
- d. The AC filters by single tuned branches for 5th, 7th, 11th and 13th harmonics.

- e) The static load by a series resistance inductance circuit.

FULL LOAD REJECTION AT INVERTER AND OF THE HVDC LINK

Soon after the load rejection the inverter AC busbar voltages and the line section capacitor voltages vary drastically peaking to 2.2 pu and 3 pu respectively. Meanwhile the DC link current decreases and settles down to a low value of about 0.4 pu as determined by the system conditions and the inverter control scheme, since the rectifier is now under minimum triggering angle control. It can be observed that as the DC link current decreases the magnitudes of the overvoltages at the inverter busbars as well as the oscillations of the line section capacitors voltages also decrease. As the DC link current settles down, the overvoltages at the inverter busbars also reach a substantial value of about 1.25 pu.

It has been observed that the magnitudes of the overvoltages with the filter capacitor values unaltered are not significantly affected by the change in line length, smoothing reactor and the Q - factor of the filter circuit. This is expected because none of these parameters drastically change the DC link current, which alone determines the magnitude of overvoltages. Therefore for the given system conditions and the inverter control scheme, the magnitude of the overvoltages can be further reduced by operating the rectifier with larger triggering angles. This can be carried out, for instance, by effecting a lower rectifier current setting immediately after the load rejection.

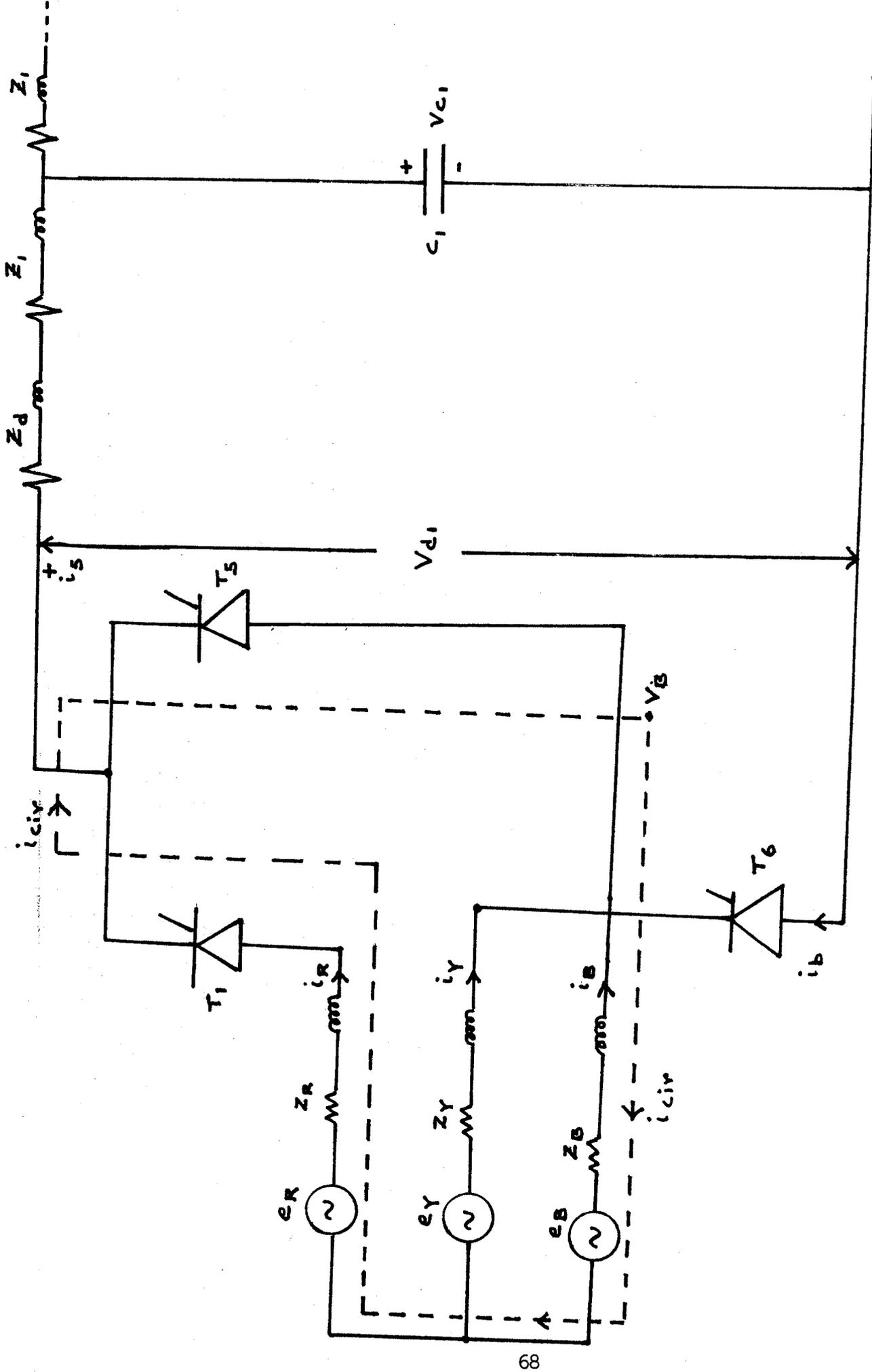
LOAD REJECTION AT AN INVERTER IN THE 3 TERMINAL HVDC SYSTEM

In this rectifier and inverter - 1 operate on constant current control while inverter - 2 operated on minimum extinction angle control. Before effecting the load rejection, the system will be in steady state condition with current settings of 1.0 pu, 0.6 pu and 0.3 pu at the rectifier, inverter -1 and inverter -2, respectively.

FOR LOAD REJECTION AT INVERTER - 1

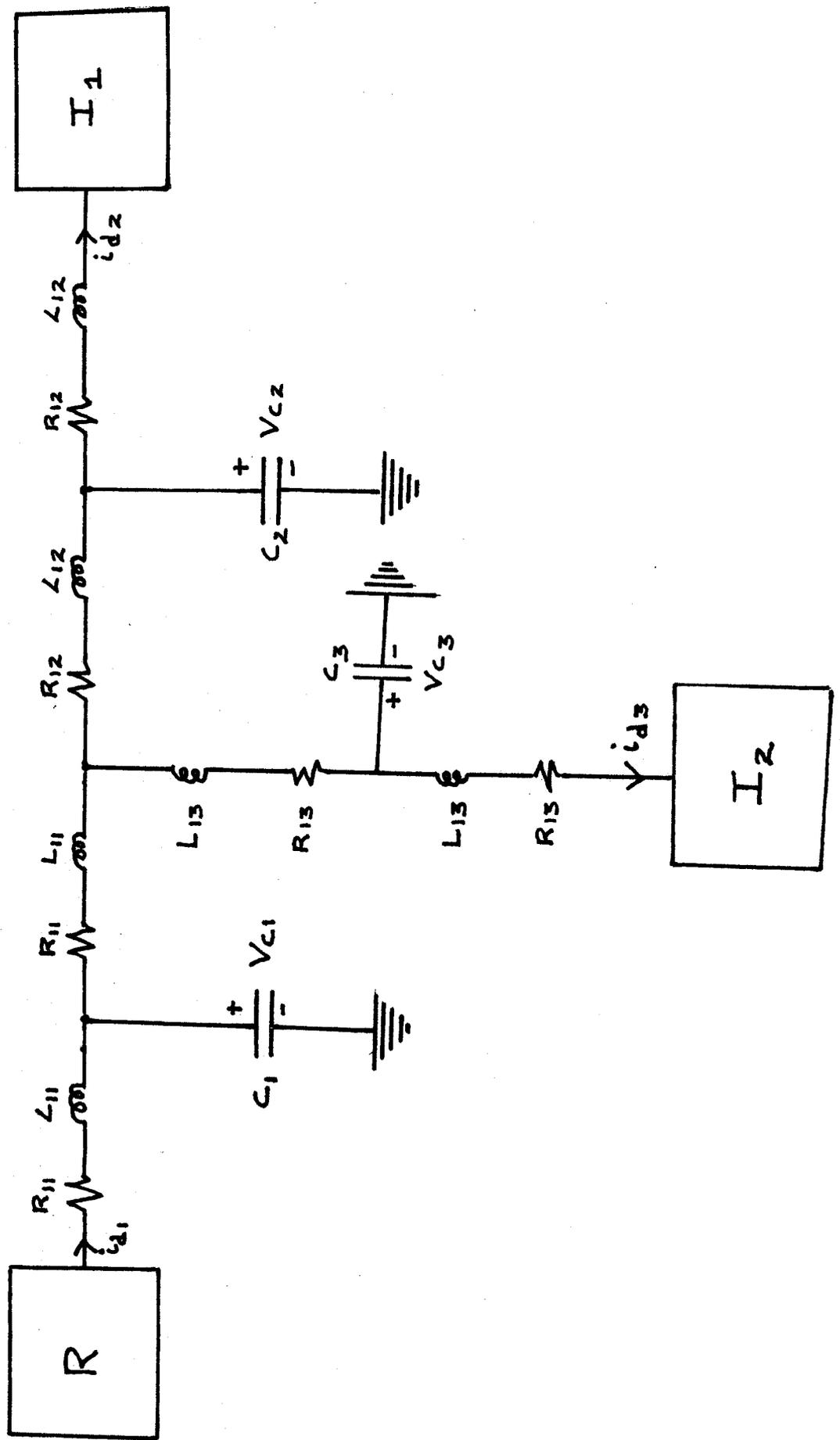
Overvoltages at the inverter-1 AC busbars are of the order of 1.1 pu and no appreciable change in the line section capacitor voltage. It can be observed that the inverter currents are maintained almost to their set values even after the load rejection. This is because the inverter currents are only a fraction of the rectifier current and the control scheme at the inverters, unlike in the case of HVDC link, are able to maintain there inverter currents. This leads of sustained over-voltages right from the instant of load rejection.

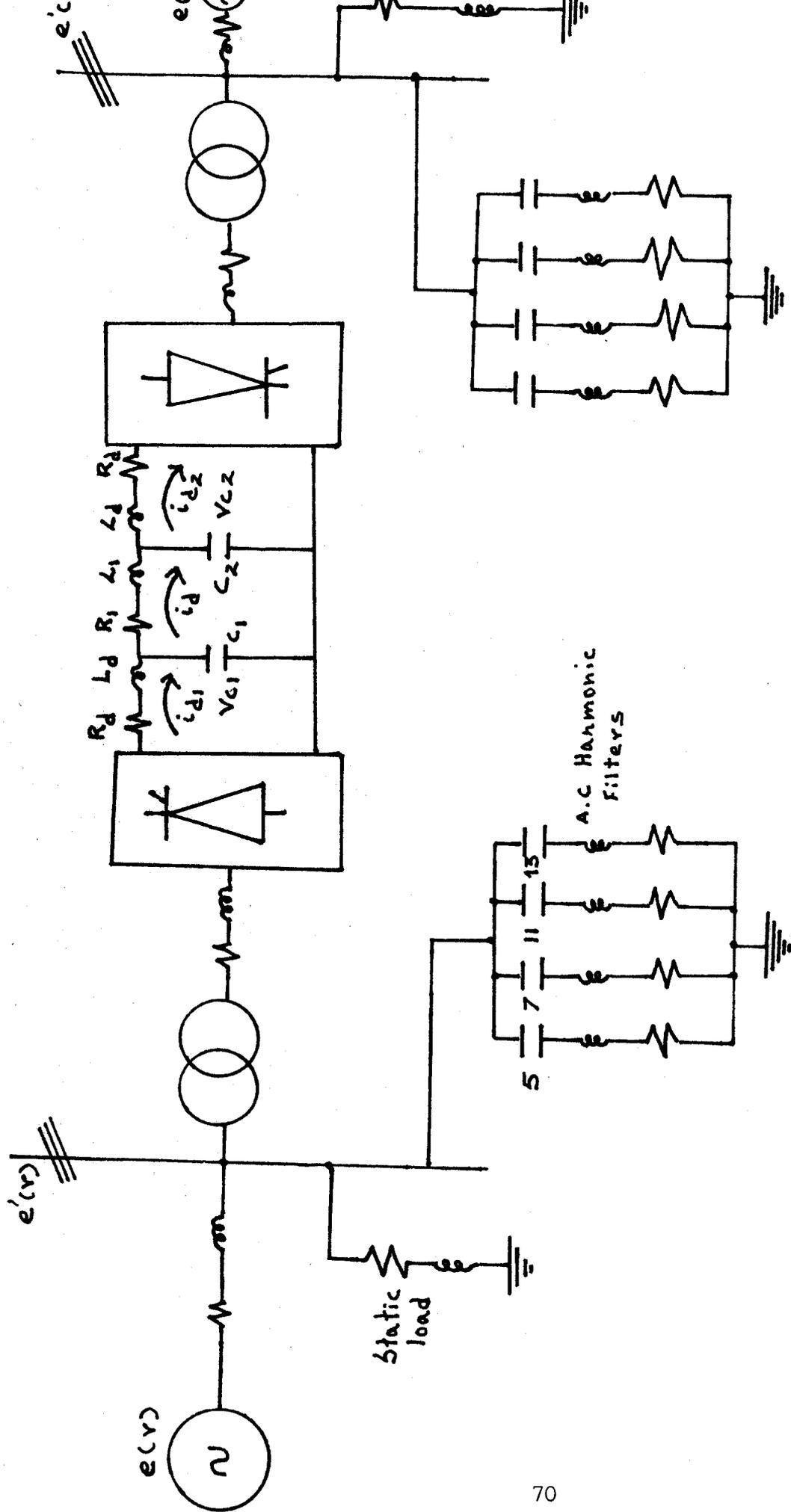
For a 3-terminal HVDC system considered, it is observed that larger step change in current settings at the inverters lead to larger oscillations of V_{c1} , V_{c2} , V_{c3} (of the order of 1.3 pu) and longer times for the currents to settle down in their set values.



CONVERTER MODEL

3-TERMINAL HVDC SYSTEM





HVDC LINK

CONCLUSION

This report of work emphasises the requirement of EHV AC or EHV DC for transmission bulk power over long distances. However, the ultimate resort is EHV AC due to its economical and operational considerations.

For choosing a shunt series compensation scheme for EHV transmission line, it is desirable to compare various possible schemes. Schemes involving compensation concentrated in a few points may be more effective than schemes with distributed compensation while also ensuring good voltage profile along the line.

The new compensation scheme suggested does not involve higher order equations and its solutions. Also, the expression is simple and it gives straight away the compensation which compares well with other methods. The method suggested is found to be equally applicable for series compensation at centre and receiving end with fairly accurate results.

In view of the fact that a.c transmission systems are well established at the present moment. This system may continue to be used for transmission of power over distance of more 500 km.

The problem of transmission and distribution is bound to increase in time to come in view of tendency to concentrate power generation in larger units and the longer distances involved. Higher and higher voltages of transmission appears to be the only feasible solution. Some of the methods under investigation are :

- a. Creating a hybrid system which carry dc and ac
- b. Use of ultrahigh frequencies ie by wireless transmission of power.

APPENDIX

NOTATIONS :

| | | |
|-------------------|---|--|
| ABCD | - | Generalised constants. |
| $A_0 B_0 C_0 D_0$ | - | Resultant generalized circuit constants with series capacitor. |
| $A_1 A_2 A_3 A_4$ | - | Components of A_0 |
| $B_1 B_2 B_3 B_4$ | - | Components of B_0 |
| E_s | - | Sending end voltage in KV |
| E_r | - | Receiving end voltage in KV |
| K | - | Ratio of E_s to E_r |
| P_r | - | Receiving end power in MW |
| $P_{r \max}$ | - | Maximum received power MW |
| R | - | Resistance of line in ohms/Km |
| Y | - | Shunt admittance of line in ho/Km |
| L | - | Inductance of line |
| θ , ϕ | - | Arguments of A_0 and B_0 resp. |
| | - | Phase angle between E_s and E_r . |

The power received is

$$P_r = \frac{E_s E_r}{B_0} \cos(\theta_0 - \theta_r) - \frac{A_0 E_r^2}{B_0} \cos(\theta_0 - \theta_r)$$

Where $A_0 = (A_1 + A_3 X_c) + j(A_2 + A_4 X_c)$

$$B_0 = (B_1 + B_c X_c) + j(B_2 + B_4 X_c) = R_0 + jX_0$$

Where $R_0 = B_1 + B_c X_c$ and $X_0 = B_2 + B_4 X_c$

In case of transmission line problems the value of θ is very small. Hence neglecting it,

$$P_{r \max} = \frac{E_s E_r}{B_0} - \frac{A_0 E_r^2}{B_0} \cos \theta$$

Making two more simple and reasonable approximations which establish their property in the end by results.

$$A_0 = A_1 + A_3 X_c ; \quad B_0 = B_2 + B_4 X_c$$

The above expression for $P_{r \max}$ reduces to the form

$$\begin{aligned} P_{r \max} &= \frac{E_s E_r}{B_0} - \frac{A_0 E_r^2}{B_0} \cdot \frac{R_0}{B_0} \\ &= \frac{E_r^2}{B_0} [K \cdot B_0 - A_0 \cdot R_0] \end{aligned}$$

Substituting for B_0 , A_0 and R_0

$$P_{r \max} = \frac{E_r^2}{(B_2 + B_4 X_c)^2} [K (B_2 + B_4 X_c) - (A_1 + A_3 X_c) \cdot (B_1 + B_2 X_c)]$$

that is

$$\begin{aligned} X_C & (-B_4^2 K - 2B_2 B_3 A_3 + B_4 B_1 A_3 + B_4 B_3 A_1) \\ & = B_2 B_4 K + B_2 B_1 A_3 + B_2 B_3 A_1 - 2B_4 B_1 A_1 \\ X_C & = \frac{B_2 B_4 K + B_2 B_1 A_3 + B_2 B_3 A_1 - 2B_4 B_1 A_1}{B_4 A_1 A_3 + B_4 B_3 A_1 - 2B_2 B_3 A_3 - B_4^2 K} \end{aligned}$$

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