CHARACTERISTICS OF HIGH VOLTAGE DIRECT-CURRENT TRANSMISSION

by

UDAI NARAIN

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

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE

1966

CERTIFICATE

Certified that the dissertation entitled ....
"Characteristics of High Voltage Direct Current Transmission"
....

which is being submitted by Sri UDAI NARAIN .... in partial fulfilment for the award of the Degree of Master of Engineering in ELECTRICAL POWER SYSTEMS ... of University of Roorkee is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

This is further to certify that he has worked for a period of ....8.....months from ..January.. to....August....1966 for preparing dissertation for Master of Engineering Degree at the University.

Signature ....
(DR. L. M. RAY)
Designation of
the Supervisor

Assoc. Professor
Electrical Engineering Department
University of Roorkee
ROORKEE

Dated October 12, 1966.

ACKNOWLEDGEMENT

Author wishes to acknowledge his profound sense of gratitude to Dr. L. Ray, Associate Professor in Electrical Engineering Department, University of Roorkee, Roorkee, whose continuous guidance and encouraging suggestions have made the presentation of the work possible in its present form. Thanks are also due to Dr. [illegible].Horigome, Sri [illegible].Ito and Mr. [illegible].Uchida of Electrotechnical Laboratory, Japan and Dr. N.G.Hingorani, of Manchester College of Science and Technology, for sending their valuable papers for ready reference.

My sincere thanks are also to Professor C.S.Ghosh, Head of the Electrical Engineering Department, University of Roorkee, Roorkee for suggesting the topic and providing various types of facilities in the department from time to time.

U. Narain
1.10.66
(U. A. NARAIN)

CONTENTS

SYNOPSIS

CHAPTER - 5 - Power Angle Characteristics

CHAPTER 6 - Stability Consideration.

SYMBOLS

Unless otherwise stated, following notations will be used:-

E_1 = r.m.s. phase to phase voltage at generator

E_2 = r.m.s. phase to phase voltage at load.

E_d, V_d = direct voltage.

I_d = direct current

V_1 = A.C. Voltage at converter transformer

V_2 = A.C. Voltage at inverter transformer.

ϕ_1, ϕ_0 = Power factor at converter transformer a.c. side.

ϕ_2, ϕ_r = Power factor on the a.c. side of inverter.

K_1, K_2 = Constants depending on connection of rectifier and inverter to be accounted with a.c. and d.c. voltage conversion.
$= \frac{3\sqrt{2}}{\pi}$ for 3 phase Connections

K_3, K_4 = Constants depending on rectifier and inverter to be accounted with a.c. and d.c. current conversion.

Z_0 = Equivalent a.c. impedance of d.c. line from sending end.

Z_r = Equivalent a.c. impedance of d.c. line from receiving end.

δ_{12} = Torque angle between machine 1 and 2.

λ = Factor relating sending end and receiving end voltage of d.c. line in a.c. equivalent circuit.

L = Total series inductance of per phase of transformer.

α = Delay angle of grid firing for rectifier.

γ = Angle of overlap.

δ = Deionisation angle of valve.

1, s = Suffix "1" or "s" represents for rectifier end.

Suffix "2" or "r" represents for inverter end.

SYNOPSIS

High voltage direct current power transmission is coming up now a days rapidly. As a matter of fact, in certain countries where sources of power are far away from load centres, d.c. transmission hasproved to be the most economical solution. This dissertation deals with the analysis of d.c. systems. A parallel a.c. & d.c. system has been assumed and analysed. The analysis hasbeen primarily devoted towards power flow and reactive power requirements of d.c. transmission systems. Stability considerations have also been discussed. The studies indicate the results in favour of possible use of a combined a.c. and d.c. transmission system.

CHAPTER - 1

CHAPTER-1

1.1. INTRODUCTION

With increased demand of power, it was essential to raise transmission voltage and distance. Additional problems came up with E.H.V. a.c. transmission. In recent years, from time to time due consideration has been given to do away problems associated with long distance a.c. transmission and an alternative d.c. transmission has been suggested. The studies have shown possible economic advantages in favour of d.c. if sufficiently great distances are involved.[1,6,2] As a matter of fact some countries where power sources are situated far away from load centres are adopting h.v.d.c. for transfer of large blocks of power and studies carried out in their d.c. research centres have shown many technical advantages of d.c. transmission over a.c. As is well known that stability of an a.c. transmission system is dependent on power per circuit and the length of transmission lines. For longer lines reactance becomes high which presents stability problems and thus for longer lines it thus becomes necessary to introduce intermediate stabilising equipments like series capacitors (in transmission lines), shunt reactors (in cables) or even intermediate switching station. Introduction of any of these equipment increases the cost of the system considerably. In d.c. transmission system the line length does not affect the stability and so it is possible to extend d.c. line length according to load requirements, without using any intermediate compensating equipment or station.

While it is economically justified to use h.v.d.c. transmission for transfer of large blocks of power,[1,7] it is not at all practicable to do away all the existing h.v.a.c. schemes only on this basis. Now a days, where the capacity of existing a.c. projects is to be increased, the new extension is done by d.c. and also for purpose of interconnection of different power systems d.c. links are used. The present studies will bring out the advantages and limitations of d.c. transmission and also its contribution towards stability improvement of the system while working in parallel with an a.c. transmission line.[13,14]

1.2. PRINCIPLE OF POWER FLOW

It is well established that A.C. is the best form of energy from generation as well as utilisation point of view. Generation of d.c. at high pressure is not possible, hence a modern d.c. transmission involves generation in a.c. form, voltage is stepped up by means of step up transformer and after converting it into d.c. by means of rectifier, electrical power is transmitted on lines and fed to the a.c. system after converting back into a.c. form by means of invertors. Voltage can be lowered at the receiving end by stepdown transformer to a distribution voltage suitable for consumers.[6] Such a scheme can be represented as shown in Fig. 1.1.

1.2.1.

In A.C. system power transmitted is given by the relation[12]

$$P_1 = \frac{E_1^2}{Z} \cos\theta - \frac{E_1 E_2}{Z} \cos(\delta_{12} + \theta)$$

For sending end, and for receiving end

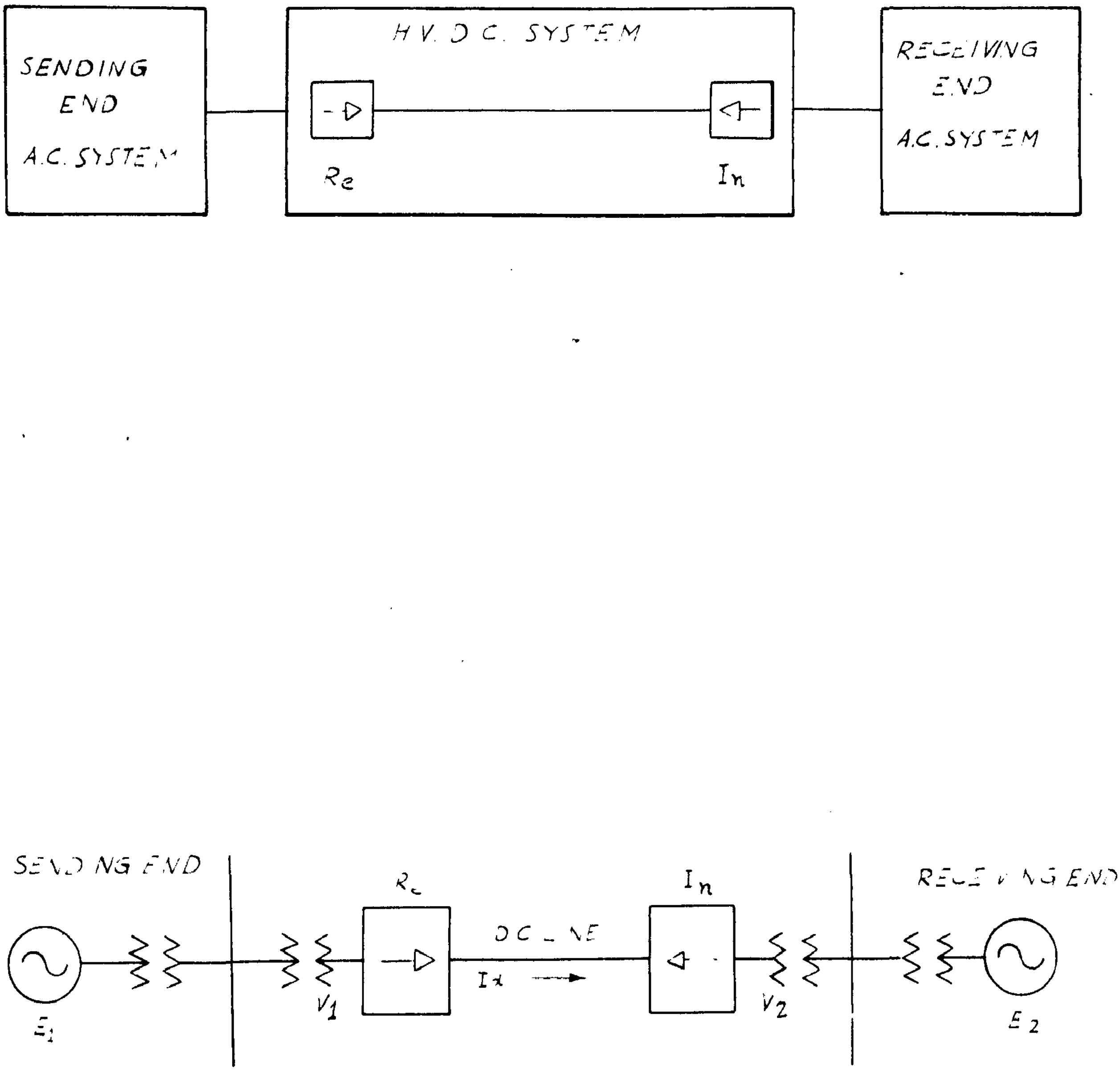


FIG 1.1 SIMPLE A.C.-D.C.-A.C. SYSTEM.

$$P_2 = \frac{E_2^2}{Z} \cos\theta - \frac{E_1 E_2}{Z} \cos(\delta_{21} + \theta)$$

Where

$$\tan\theta = \frac{X}{R}$$

E_1 & E_2 are the voltages at two ends of transmission lines

X = Line reactance

R = Line resistance

δ_{12} = Electrical Angle between two voltages also known as torque angle.

If $R << X$ i.e.,

if the resistance of the line is very small as compared with the reactance the above expressions reduce to

$$P_1 = P_2 = P_{ac}$$

$$P_{ac} = \frac{E_1 E_2}{X} \sin\delta_{12} \qquad \ldots\ldots\ldots\ldots 1.1.$$

In a d.c. system the transmitted power is given by[13]

$$P_{d.c.} = \frac{Ed_1 (Ed_1 - Ed_2)}{R} \qquad \ldots\ldots\ldots\ldots 1.2.$$

Where Ed_1 and Ed_2 are direct voltages on the rectifier and inverter ends respectively.

Equation 1.2. shows that d.c. power is proportional to the difference of voltages while as the a.c. power is proportional to product of voltages at two ends.

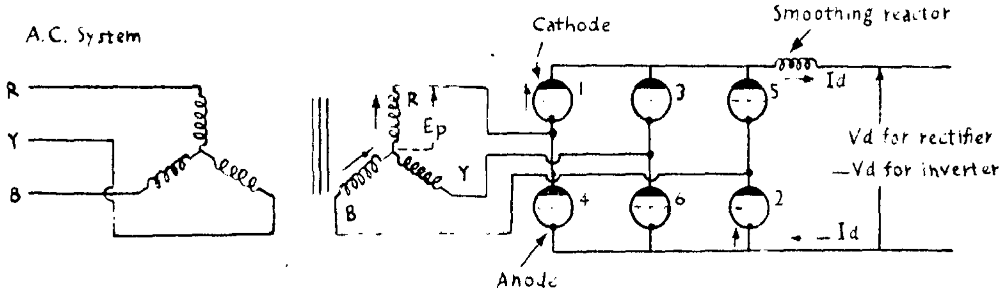
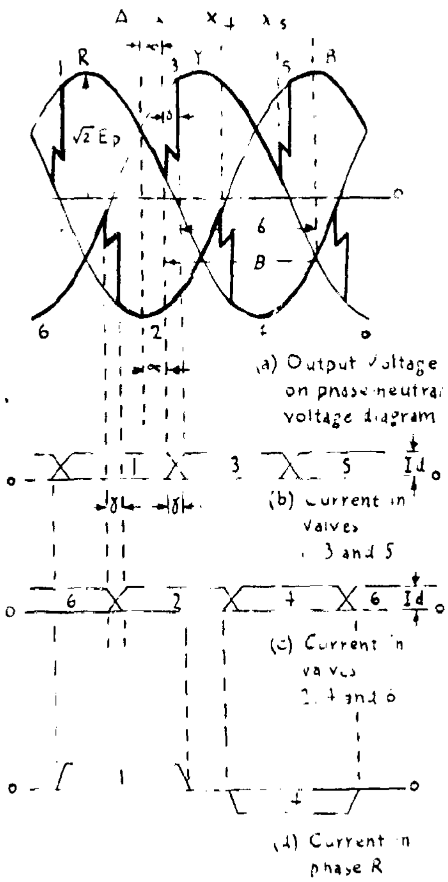


FIGURE 1.2

VALVE ARRANGEMENT



OPERATION AS RECTIFIER

FIGURE 1.3

1.3. MAIN EQUIPMENTS FOR D.C. TRANSMISSION

The description and working principle of convertors can be found in any standard text book (Reference 1,2,6), here only a brief resume is given to enlist the accessories and their behaviour for easy reference.

i) Convertor Transformer:

The convertor transformer serves the purpose of isolating the a.c. and d.c. systems, It also provides voltage suitable to valves for conversion but even if a suitable voltage for valve is available, a one to one ratio transformer is required for isolation purposes.

ii) Operation of Bridge Convertor:

A three phase bridge connection as in fig. 1.2, has been universally accepted, as the best connection for h.v.d.c. convertors. This is mainly because the bridge connection provides the best utilisation of the transformer. The current and voltage wave forms are shown in Fig. 1.3. The direct voltage is shown by the thick line.

In a rectifier the anode switching can be delayed or accelerated by controlling the grid operation. The relation of conversion for a delay angle α is given below:

$$V_d = \frac{3\sqrt{2}}{} E . \cos\alpha \qquad ....(1.3)$$

Where

E is phase to phase r.m.s. voltage.

α is grid control angle or delayed firing angle, and

V_d is the direct voltage.

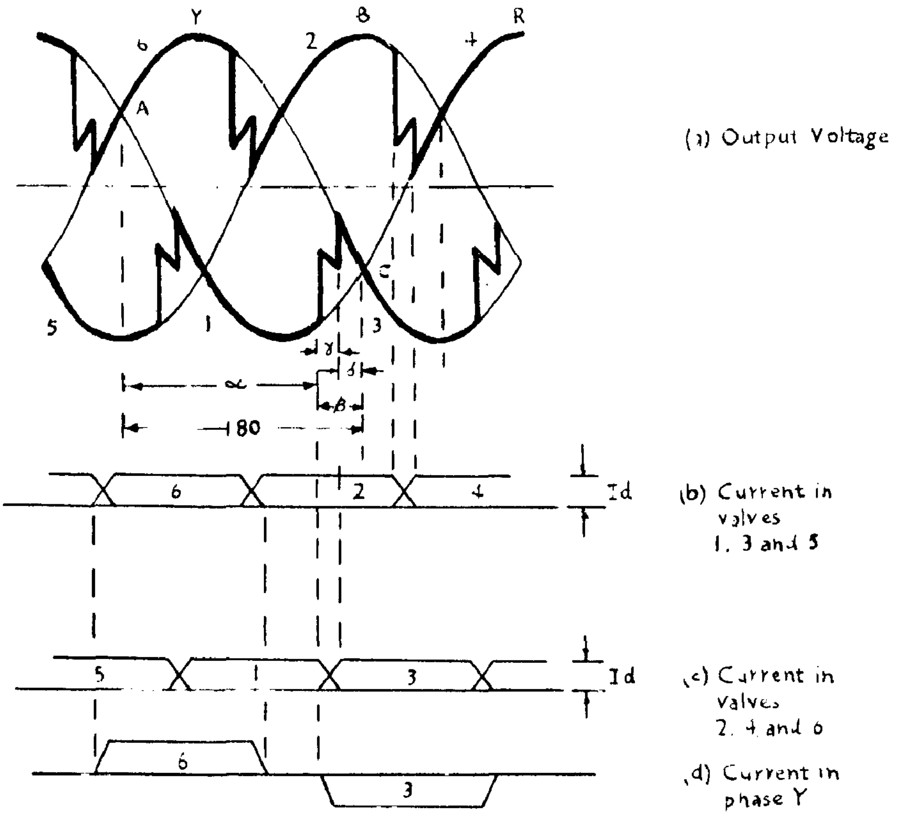


FIGURE 1.4

OPERATION AS INVERTER

Equation 1.3. shows that by increasing α, d.c. voltage goes on decreasing, passes through zero and after 90° the direction of power flow reverses, the power being now fed into a.c. system from d.c. line and the convertor is said to be acting as invertor.

When one valve stops conducting, the current does not suddenly drops to zero, due to reactance of transformer etc., but it takes a finite ~~time~~ angle γ to drop to zero.[2] Similarly when next valve starts conducting its current does not attain its full value Id immediately after firing. As shown in Fig. 3 the period γ is known as overlap ~~time~~ angle. There is a reduction of direct voltage due to this overlap. The voltage relation is given by the following expression.

$$V_d = \frac{3\sqrt{2}}{\pi} E \quad \frac{\left[\cos\alpha + \cos(\alpha+\gamma)\right]}{2} \qquad \ldots 1.4.$$

In relation 1.4, Vd the average output voltage is calculated by integrating and averaging the waveform.

If the angle γ is neglected then

$$V_d = \frac{3\sqrt{2}}{\pi} E. \cos\alpha$$

$$= V_o \cos\alpha$$

where Vo is the maximum no load output voltage with $\alpha = 0$.

To derive the equation governing commutation angle,[6] consider, say, commutation from valve 1 to 3 when valve 3 fires, it causes a short circuit between phases Y and phases R. The increasing short circuit current flows against the forward current Id in valve 1 untill current reduces to zero in valve 1 and increases to Id in valve 3. The equation of this short-circuit is

$$2L \frac{di_s}{dt} = \sqrt{2}\, E \sin \omega t.$$

where "is" is the instantaneous short circuit current. Integration and solution for the conditions,

When $\omega t = 0$, $-i_s = Id$ gives

$$Id = \frac{E}{\sqrt{2}\,\omega L} \left[\cos\alpha - \cos(\alpha + \gamma) \right] \quad \ldots\ldots(1.5)$$

iii) Operation of a Bridge Inverter:[9]

When the angle of delay of a converter exceeds 90°, the average voltage becomes negative, now if an external d.c. voltage forces the current in a direction in which the valves conduct against this negative voltage, the converter receives power and becomes an inverter. The firing angle then is known as angle of advance firing and is given by

$$\alpha = (90 - \beta)$$

It is important to note that the current is still flowing in the same direction, forced by rectifier voltage, Fig. (1.4).

During inverter operation it is important that commutation is complete, before the following voltage zero, i.e. commutation from valve 1 to 3, must be over before point c, Fig. (1.4). The point of change in sign of commutating voltage VRL. In fact the commutation must be complete a certain extinction angle δ = about 10 degrees, before voltage zero. This is due to fact that when a valve is conducting its grid is surrounded by ionised mercury vapour[2] and is ineffective, since the state of ionisation in a valve does not collapse suddenly at the end of current conduction, but takes certain time to decay. This time is the time required for deionisation of the outgoing valve, so that it regains its grid control, otherwise valve 1 will take the current back from valve 1 and result into a fault known as commutation failure.

It is therefore, important to give the inverter a sufficient angle of advance $\beta = \delta + \gamma$. Therefore grid control is obviously an essential feature for an inverter operation.[3] The availability of an a.c. supply is also an essential requirement for an inverter.

Since inverter is merely a rectifier with delay angle α greater than 90^o. The same equations will apply to the inverter operation, for convenience, inverter equations are given in terms of angle of advance firing β and extinction angle δ.

The expressions for direct voltage and current for an inverter are[1,2,6]

$$Vd = \frac{3\sqrt{2}}{\pi} E \left[\frac{(\cos\beta + \cos\delta)}{2} \right] \qquad .....(1.6)$$

$$Id = \frac{E}{\sqrt{2}\ \omega L} (\cos\delta - \cos\beta) \qquad .....(1.7)$$

iv) Smoothing Reactor[1]

Fig. 1.3 shows that the d.c. voltage contain ripples and output voltage is not perfectly smooth. In order to reduce the ripple in the d.c. output from the convertors and at the same time to limit the rate of rise of the current, a smoothing reactor is usually connected on the d.c. side of the transmission line. This reactor has normally an inductance of few Henry and is designed as an air-core reactor surrounded by an iron core.

V) VALVE CONNECTION:[39]

Mercury arc valves are not available for very high voltage rating. Maximum valve rating at present does not exceed 200 KV. HV. D.C. terminal stations may contain more than one valve. There is general tendency now a days that where a d.c. terminal station is to contain more than one valve, these will be connected in series(Figure 15), in contradiction to universal practice of parallel connection in case of a.c. stations. This is because of the fact that series connection of valves facilitates taking 'out' and 'in' of a valve in the case it develops a fault. A by-pass valve is also connected across d.c. terminals to help putting 'in' or 'out' of a particular valve in the circuit.

1.4. TYPES OF H.V.D.C. SYSTEMS:

1.4.1. SIMPLE A.C.-D.C.-A.C. SYSTEM:[1,2]

In the system shown in figure 1.6(a) one terminal d.c. transmission is used and earth is used as a return path.

Two terminal d.c. transmission system (shown in Figure 1.6(b), makes use of both positive and negative polarity. Other arrangement is used as two terminal d.c. transmission with mid point earthed as shown in figure 1.6(c). The obvious advantage of the later is that when one terminal develops a fault, the supply of power can be continued through the other terminal and earth.

1.4.2. PARALLEL A.C.-D.C. SYSTEM:[13,14]

In a parallel a.c. and d.c. system as shown in figure 17, power is transmitted jointly by a.c. and d.c. lines and total

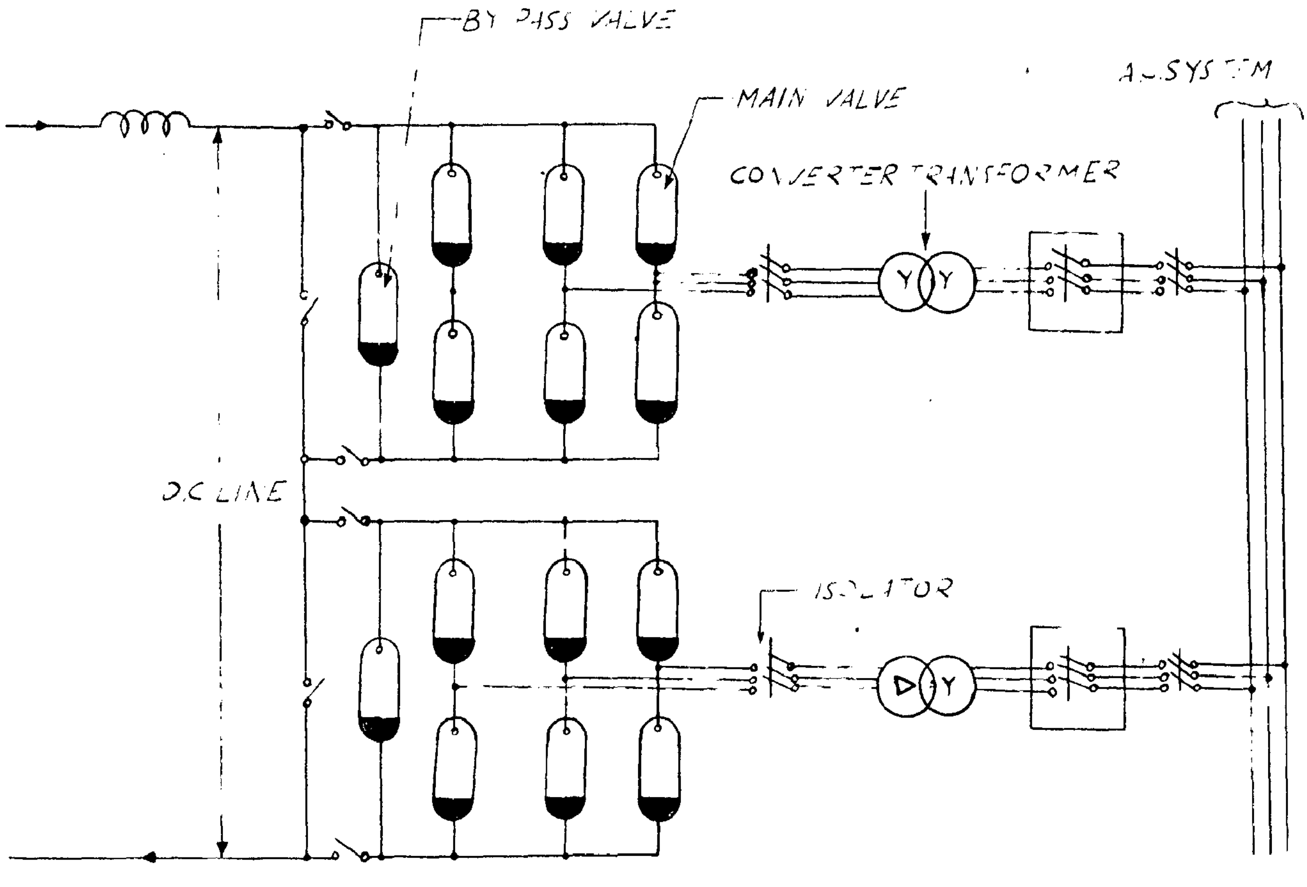


FIGURE 1.5 MAIN CIRCUIT DIAGRAM OF H.V. D.C. STATION
WITH TWO CONVERTERS IN SERIES

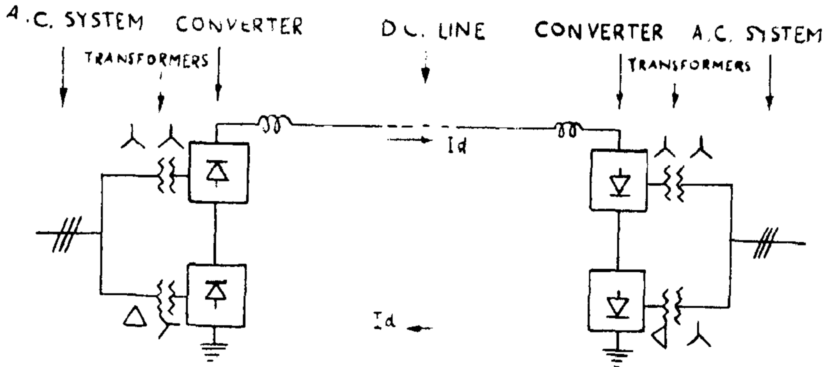


FIGURE 1.6 (a)

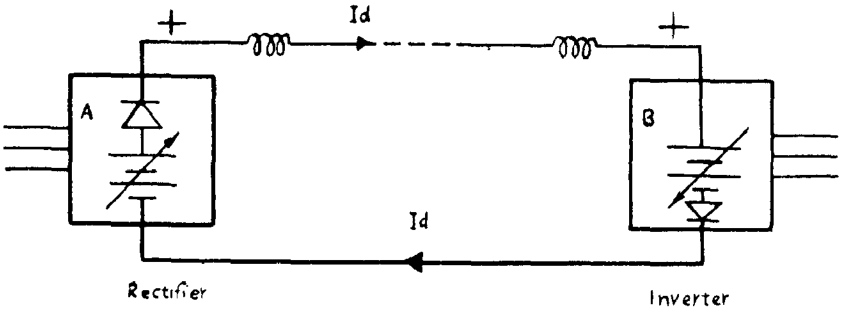


FIGURE 1.6 (b)

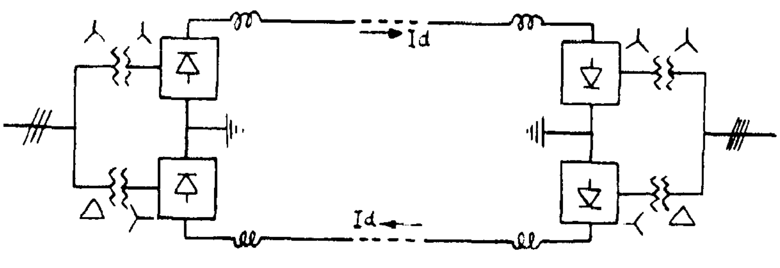


FIGURE 1.6 (C)

TYPES OF H.V.D.C. SYSTEMS

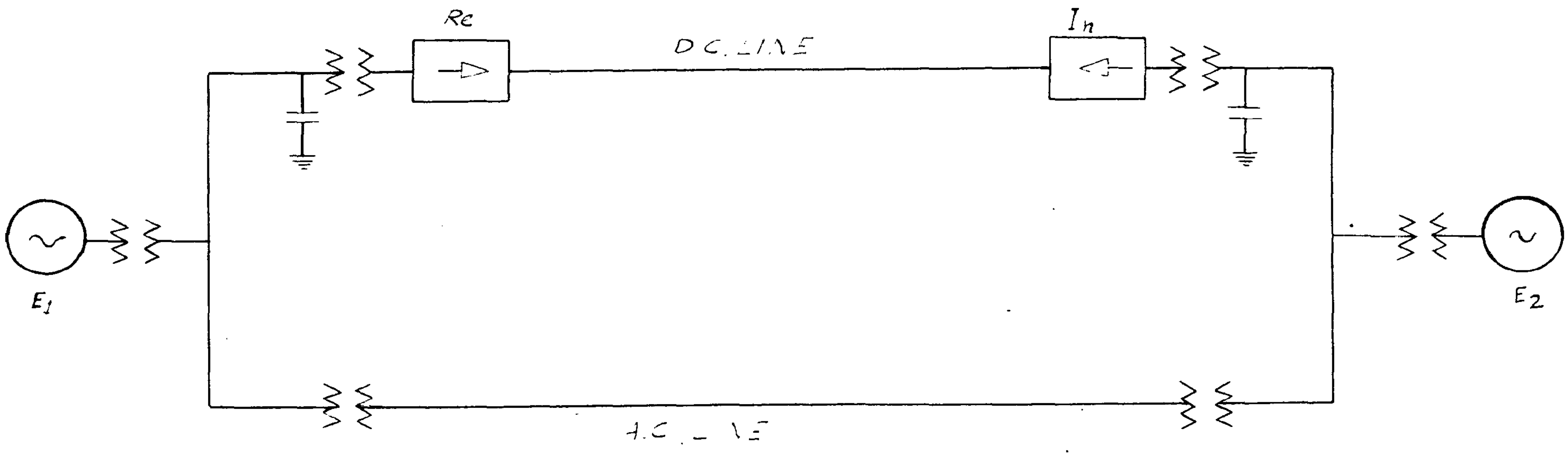


FIG 1.7 PARALLEL A.C AND D.C SYSTEM

transmitting capacity is divided between the two.

1.5. CONTROL OF CONVERTERS: (2,28,16)

Since the output voltage of converters can be varied from positive to negative by means of grid control, the system as a whole can be controlled in a variety of ways to obtain the desired characteristics. Selection of the converter characteristics therefore should be such as to meet the requirement of regulation and protection. The theory of converter operation shows that direct voltage and current are function of α and γ_s for rectifier and β, γ_r and δ for invertor. By varying these quantities in a suitable way, the converters can be given any desired characteristics over its range of operation.

The converters are generally controlled in two ways, constant current control and constant firing angle control. The trend in a d.c. transmission is that power transmission in controlled by the rectifier end and so rectifiers are generally provided with constant current control. Thus if the current exceeds a particular set value, the delay angle increases thus decreasing output voltage, this prevents the current from rising much above the set values. The invertor operation on the other hand, has to be such that it assures safety of operation. So invertors are provided with a control such that the firing angle is always minimum to keep the reactive power requirement within limits. This angle is kept constant. This type of control is referred as constant firing angle control. Invertors can also be provided with a constant current regulator. Then if current drop in a set value, firing angle is increased more than what is necessary for constant firing angle control.

CHAPTER-2

ANALYSIS OF D.C. TRANSMISSION

2.1. INTRODUCTION

D.C. link is an asynchronous tie line interconnecting two a.c. systems. The rectifier and invertor have non-linear characteristics therefore d.c. system cannot be completely represented by reactive and resistive networks like a.c. system. It has not yet been possible to obtain analytical expressions for complete system including generation at a.c., transmission at d.c. & utilisation at a.c. voltage. However, methods have been suggested to analyse such system separately for sending and receiving ends. In one method, Dr. N.G.Hingorani, suggests that from sending end a.c. side, the rectifier is considered as a load which consumes active and reactive power and from receiving end a.c. side the invertor is considered to be a generator, which has to supply active and reactive power. This is shown in Figure 2.1.

2.2. EQUIVALENT CIRCUITS[4,5]

Dr. T.Horigome has suggested a method to analyse the d.c. system by means of two equivalent circuits - one suitable for sending end and the other for receiving end. These circuits are shown in Fig. 2.2. At sending end the current is lagging voltage. This effect is shown by inductive reactance in Figure 2.2(a). At receiving end, current is leading the voltage and its effect is shown by capacitive reactance in Figure 2.2(b). For an a.c.- d.c.-a.c. system analytical expressions can be laid down with the help of the equivalent circuits of Figure 2.2. Following assumptions will however be made :-

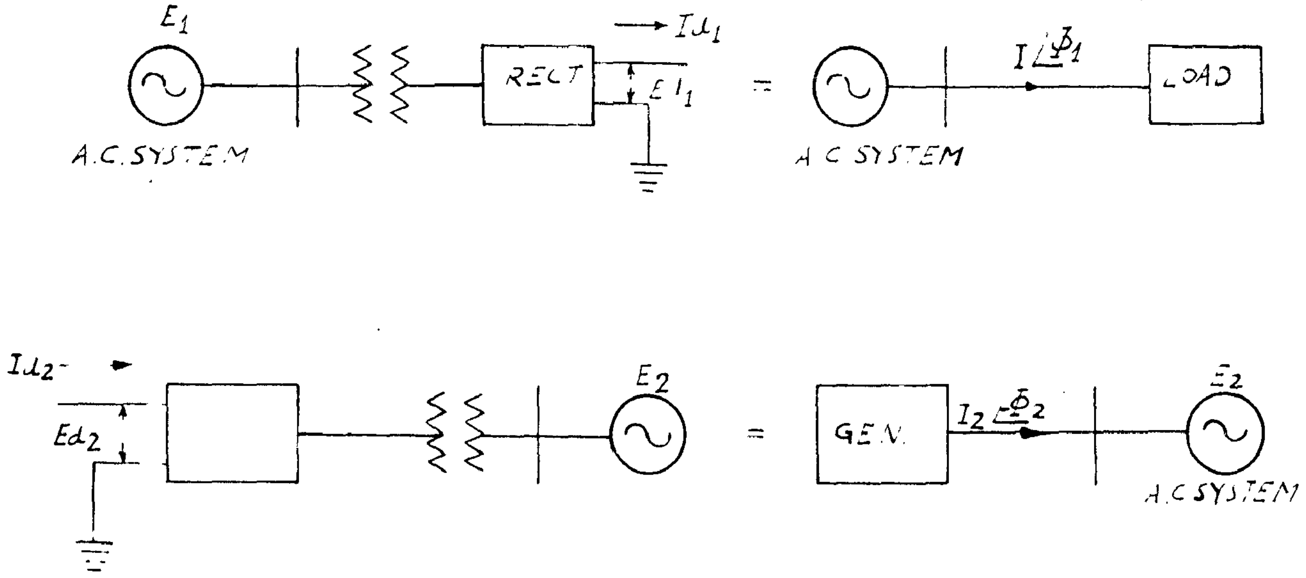
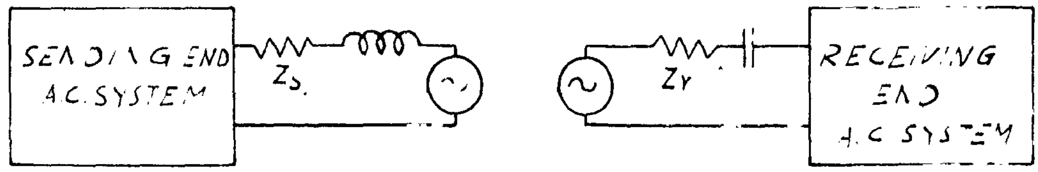


FIGURE 2.1 RECTIFIER AND INVERTER CONSIDERED AS LOAD AND GENERATOR



(a) (b)

FIGURE 2.2

(1) The a.c. voltages at the two ends of transmission line are purely sinusoidal with each phase balanced.

(2) Direct current contains no ripple.

2.3. ANALYTICAL EQUATIONS

The hypothetical system is shown in Fig. 2.3.

In fig. 2.4. is shown the equivalent circuit for the link between the a.c. system at the sending end and the d.c. circuit in accordance with the theory given by Dr. Horigome.

Direct voltage and current are given by the following equations:[1,2,6,7,8]

$$Ed_1 = K_1 V_1 \cos \alpha \qquad \text{.......2.1.}$$

$$Ed_2 = K_2 V_2 \cos \beta \qquad \text{.......2.2.}$$

$$Id_1 = \frac{V_1}{\sqrt{2}\,\omega L_1}\left[\cos \alpha - \cos(\alpha+\gamma)\right]$$

$$Id_2 = \frac{V_2}{\sqrt{2}\,\omega L_2}\left[\cos \delta - \cos \beta\right]$$

If V_1 and V_2 are a.c. voltages at the convertor and inverter transformers respectively, then in the a.c. equivalent circuit ~~the voltage~~ for sending end the voltage at the far end becomes $\frac{V_2}{\lambda}$

Where λ is a factor defined by

$$\lambda = \frac{K_1 \cos \alpha}{K_2 \cos \beta} \qquad \text{....2.3.}$$

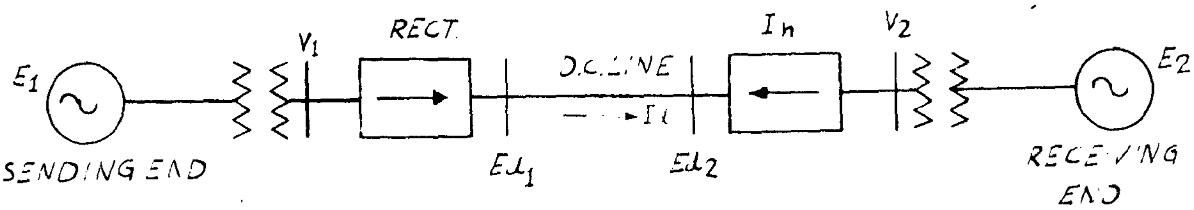


FIGURE 2.3 (a)

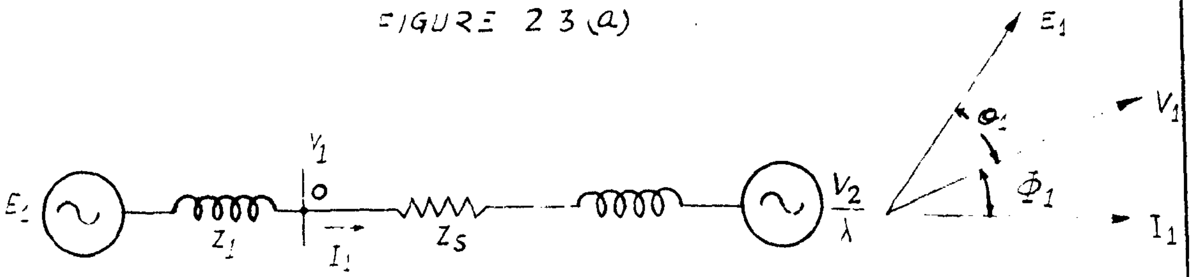


FIGURE 2·3(b). EQUIVALENT CIRCUIT FOR THE LINK BETWEEN SENDING END A.C. SYSTEM AND D.C CIRCUIT.

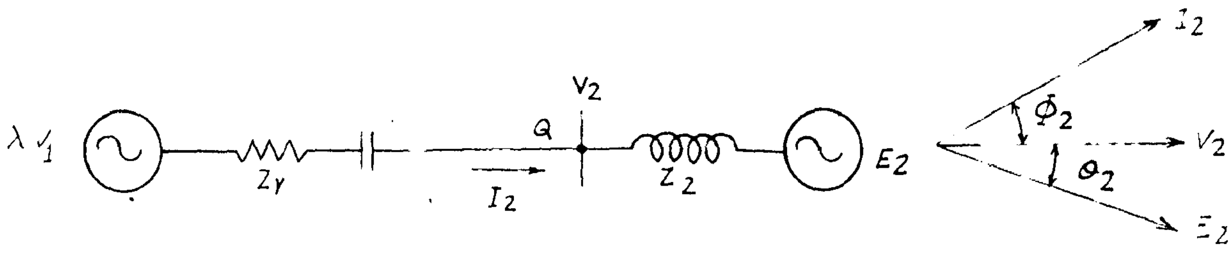


FIGURE 2·3(C) EQUIVALENT CIRCUIT FOR THE LINK BETWEEN THE D.C. CIRCUIT AND THE RECEIVING END A.C. SYSTEM.

Let Id be the current through d.c. line, and R the line resistance, then total d.c. drop

$$\text{D.C. drop} = \left[\frac{3}{\pi}(X_c + X_r) + R\right] Id \qquad \ldots 2.4.$$

from equation 2.1. it follows that

$$(\text{D.C. Voltage}) = K_1(\text{A.C. Voltage})\cos\alpha \qquad \ldots 2.5.$$

$$\text{A.C. Voltage} = \frac{\text{D.C.Voltage}}{K_1 \cos\alpha}$$

and $\frac{I_{a.c.}}{I_{d.c.}} = K_4$

The equivalent a.c. impedance is given by

$$Z\ \text{a.c. (equivalent)} = \frac{\text{A.C. drop(equivalent)}}{\text{A.C.Current(equivalent)}} \qquad \ldots 2.7.$$

$$= Zs$$

in equation(2.7.) substituting from 2.4. & 2.6.

$$Z_s = \frac{\left[\frac{3}{\pi}(X_c + X_r) + R\right] Id/K_1 \cos\alpha}{K_4\ Id}$$

$$= \frac{\frac{3}{\pi}(X_c + X_r) + R}{K_1 K_4 \cos\alpha} \qquad \ldots 2.8.$$

Since at sending end I lags E by ϕ_1

$$\therefore\ Zs = \frac{\frac{3}{\pi}(X_c + X_r) + R}{K_1 K_4 \cos\alpha}\, e^{+j\phi_1} \qquad \ldots 2.9.$$

Ratio of currents on a.c. and d.c. side is given by

$$\frac{I_{ac}}{I_{dc}} = K_4 = \frac{\sqrt{6}}{\pi} \cdot \frac{\sqrt{\left[\cos 2\alpha - \cos 2(\alpha+\gamma_s)\right]^2 + \left[2\gamma_s + \sin 2\alpha - \sin 2(\alpha+\gamma_s)\right]^2}}{4\left[\cos\alpha - \cos(\alpha+\gamma_s)\right]}$$

... 2.10

The quantity within square root is approximately equal to 1 under normal operation, so

$$\frac{I\ a.c.}{I\ d.c.} = K_3 = \frac{\sqrt{6}}{\pi} \qquad \ldots 2.10(a)$$

Considering now the sending end system as shown in Figure 2.5.(b), Z_1 is the impedance of the branch shown in Fig.

Writing current equations at Node O,

$$E_1 Y_1 + Y_o \frac{V_2}{\lambda} = I_1 \qquad \ldots 2.11.$$

Where $I_1 = K.Id$ (Ia.c. = K.Id.c.).

$$\dot{Z}_1 = |Z_1| \angle \varphi_1$$

$$\dot{Z}_o = |Z_o| \angle \phi_1$$

$$\dot{Y}_1 = \frac{1}{\dot{Z}_1} = |Y_1| \angle -\varphi_1$$

$$\dot{Y}_o = \frac{1}{\dot{Z}_o} = |Y_o| \angle -\phi_1$$

Taking I_1 as reference, the vector relationship is shown in vector diagram

$$\dot{V}_1 = |V_1| \angle \phi_1$$

$$\dot{E}_1 = |E_1| \angle \phi_1 + \theta_1$$

Substituting in eqn. 2.11. we get

$$E_1 Y_1 \angle \phi_1 + \theta_1 - \varphi_1 + \frac{V_2}{\lambda} Y_o \angle \phi_1 = K.Id. \qquad \ldots 2.12.$$

In equation (2.12) right hand side has only real part so, separating real and imaginary parts and equating the imaginary part to zero, we get two equations.

$$E_1Y_1 \cos(\phi_1 + \theta_1 - \varphi_1) + \frac{V_2}{\lambda} Ys \cos\phi_1 = K\, Id \qquad ..(2.13)$$

$$E_1Y_1 \sin(\phi_1 + \theta_1 - \varphi_1) + \frac{V_2}{\lambda} Ys \sin\phi_1 = 0 \qquad ..(2.14)$$

Angle ϕ_1 is defined as

$$\cos\phi_1 = \frac{1}{2}\left[\cos\alpha + \cos(\alpha+\gamma_s)\right] \qquad ..(2.15)$$

For receiving end, equivalent circuit is shown in Figure 2.3(c).

Analysis of the receiving end can be carried out in the similar way.

On the basis of eqn. 2.9, we can write

$$Er = \frac{\frac{3}{\pi}(X_e + X_r) + R}{K_2K_3 \cos\beta} e^{-j\phi_2} \qquad ..(2.16)$$

The ratio of current on a.c. and d.c. side of invertor can be expressed as $\frac{I_2}{I_d} = K_3$

$$K_3 = \frac{\sqrt{6}}{\pi} \cdot \frac{\sqrt{\left[\cos 2\beta - \cos 2(\beta-\gamma_r)\right]^2 + \left[2\gamma_r + \sin 2(\beta-\gamma_r) - \sin 2\beta\right]^2}}{4\left[\cos(\beta-\gamma_r) - \cos\beta\right]} \qquad ..(2.17)$$

Under normal operating conditions quantity within square root becomes = 1

therefore $\frac{I_2}{I_d} = K_3 = \frac{\sqrt{6}}{\pi}$ ..(2.17a)

Writing current equations at node Q.

$$I_2 + \lambda V_1 Y_r = E_2Y_2$$

$$E_2Y_2 - Y_r V_1 \lambda = I_2 = K.Id \qquad ..(2.18)$$

Where $I_2 = K.Id$

Taking I_2 as reference, vector relations are shown in figure 2.3.(c).

$$\dot{Y}_2 = |Y_2| \angle -\varphi_2$$

$$\dot{Y}_r = |Y_r| \angle \phi_2$$

$$\dot{V}_2 = |V_2| \angle -\phi_2$$

$$\dot{E}_2 = |E_2| \angle -\phi_2 - \theta_2$$

Equation 2.18 becomes

$$E_2 Y_2 \angle -\phi_2 - \theta_2 - \varphi_2 \quad - Y_r V_1 \lambda \angle -\phi_2 = K\ Id \qquad ..2.19$$

equation 2.19 can be resolved into real and imaginary parts as.

$$E_2 Y_2 \text{ Cos } (\phi_2 + \theta_2 + \varphi_2) - Y_r V_1 \lambda \text{ Cos } \phi_2 = K\ Id \qquad ......2.20.$$

$$Y_r V_1 \lambda \text{ Sin } \phi_2 - E_2 Y_2 \text{ Sin}(\phi_2 + \theta_2 + \varphi_2) = K\ Id \qquad ...2.21$$

The relation between angle ϕ_2, angle of overlap and current of invertor is

$$\text{Cos } \phi_2 = \tfrac{1}{2} \left[\text{Cos } \beta + \text{Cos}(\beta - \gamma_r) \right] \qquad ...2.22$$

Voltage Ed_1 at the sending end of d.c. transmission line is[1]

$$Ed_1 = K_1 V_1 \text{ Cos } \alpha - \frac{3}{\pi} X_c.Id \qquad ...2.23$$

Voltage Ed_2 at the receiving end of transmission line is[1]

$$Ed_2 = K_2 V_2 \text{Cos } \beta + \frac{3}{\pi} Xr\ Id \qquad ...2.24$$

Subtracting Eqn. 2.24 from 2.23, we get the voltage drop on the d.c. transmission line.

$$Ed_1 - Ed_2 = K_1V_1 \cos\alpha - K_2V_2 \cos\beta - \frac{3}{\pi} Id(X_c + X_r)$$

But $Ed_1 - Ed_2 = R\, I_d$ ....2.25.

Therefore the equation coupling both equivalent circuits is obtained as

$$K_1V_1 \cos\alpha - K_2V_2 \cos\beta = \left[\frac{3}{\pi}(X_c + X_r) + R\right] Id \qquad ..2.26$$

2.4. ANALYSIS OF PARALLEL A.C. D.C. SYSTEM 45"

2.4.1. SENDING END ANALYSIS

On the basis of the equivalent circuit theory, as explained earlier, parallel A.C. and D.C. system of figure 1.7 can be simplified as Figure 2.4(a) for sending end and 2.4(b) for receiving end.

Let $\dot{Y}_1 = \frac{1}{Z_1} \angle{-\varphi_1}$

$\dot{Y}_{2s} = \frac{1}{Z_{2s}} \angle{-\varphi_2}$ — As represented in Fig. 2.4(a).

$\dot{Y}_c = \frac{1}{Z_c} \angle{\phi_1}$

Taking Ida as reference vector

Where Ida = (K.Id.c.) = A.C. equivalent current in d.c. line

k = constant

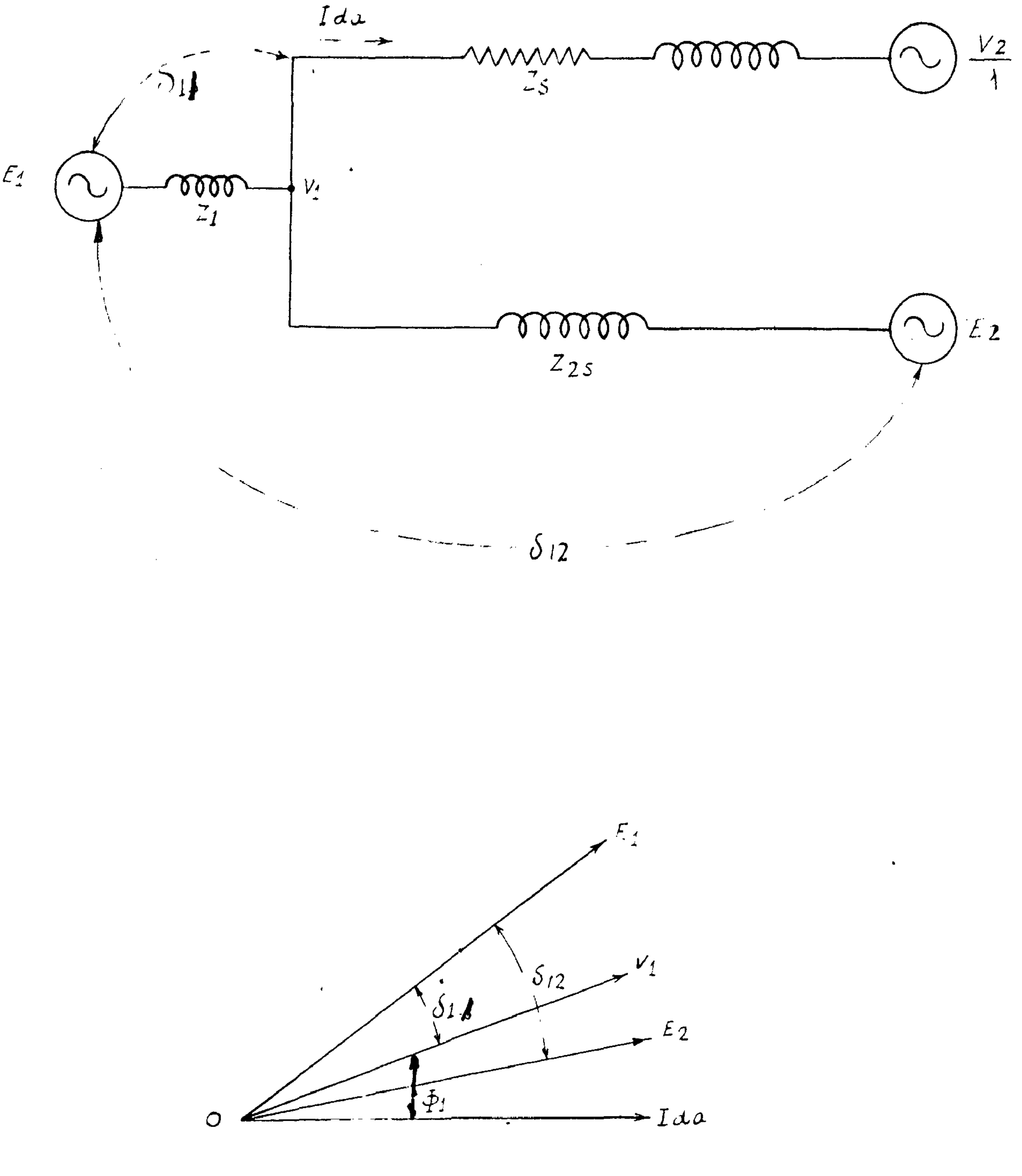
$\dot{V}_1 = |V_1| \angle{\phi_1}$

$\dot{E}_1 = |E_1| \angle{\phi_1 + \delta_1}$

$\dot{E}_2 = |E_2| \angle{\phi_1 + \delta_1 - \delta_{12}}$

Now writing the current equations at node V_1

$$E_1Y_1 - Y_c \frac{V_2}{\lambda} - E_2 Y_{2s} = KId \qquad ...2.27.$$



EQUIVALENT CIRCUIT AND VECTOR DIAGRAM OF FIGURE 1.7 FOR SENDING END ANALYSIS.

FIGURE 2.4(a)

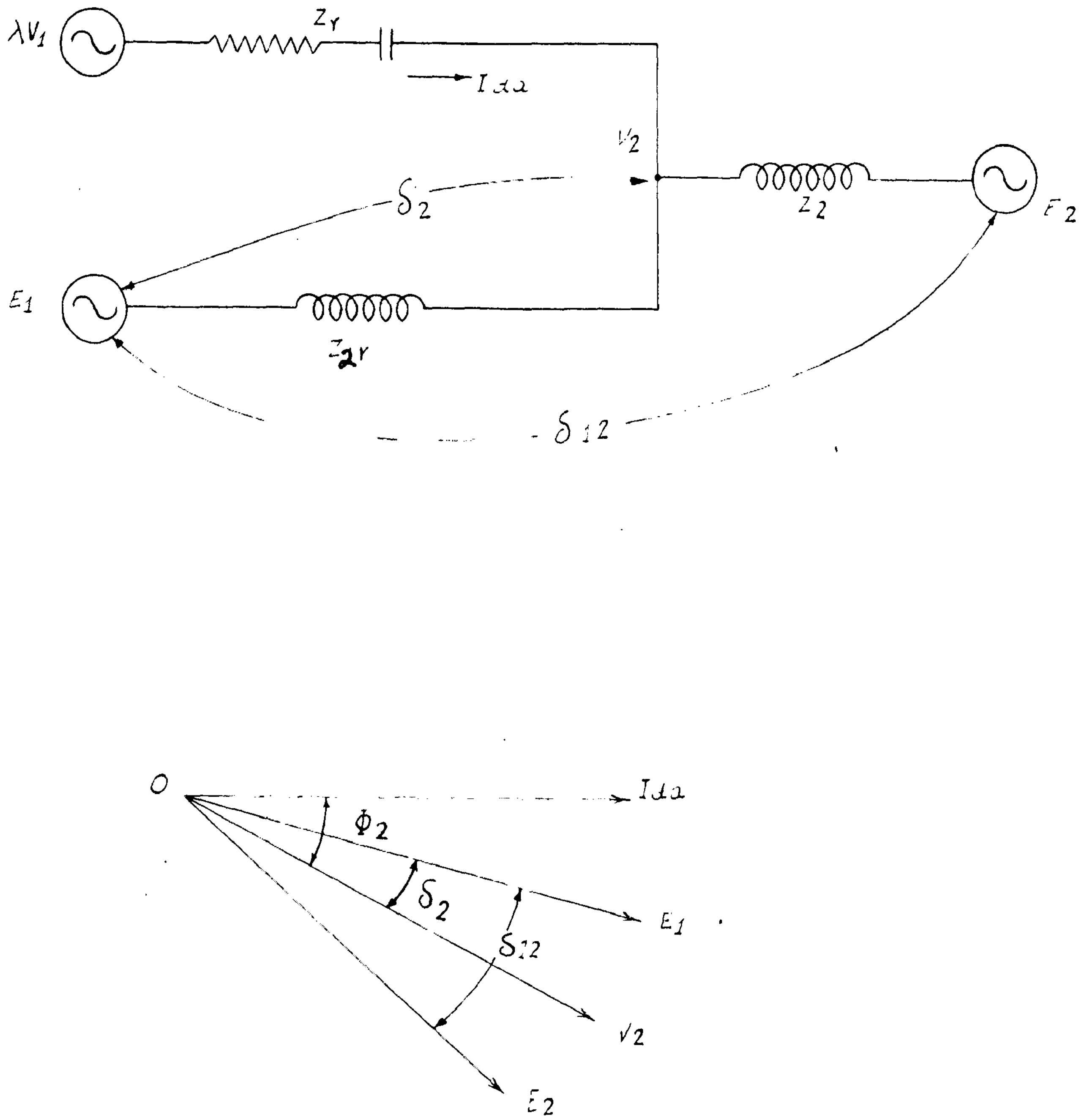


FIGURE 2.4 (b)
EQUIVALENT CIRCUIT AND VECTOR DIAGRAM OF
FIGURE FOR RECEIVING END ANALYSIS.

$$E_1Y_1 \angle \phi_1 + \delta_1 - \varphi_1 \;\; - E_2 Y_{2s} \angle \phi_1 + \delta_1 - \delta_{12} - \varphi_2 \;\; - Y_o \frac{V_2}{\lambda} \angle +\phi_1 = KId \;..2.28.$$

Separating real and imaginary parts of equation 2.28 and since direct current has only real value, equating imaginary part to zero, we get:

$$E_1Y_1 \text{ Cos}(\phi_1+\delta_1-\varphi_1) - E_2Y_{2s} \text{ Cos}(\phi_1+\delta_1 - \varphi_2 \quad) - Y_o \frac{V_2}{\lambda} \text{ Cos } \phi_1 = KId \;.(2.29)$$

$$E_1Y_1 \text{ Sin}(\phi_1+\delta_1-\varphi_1) - E_2Y_{2s} \text{ Sin}(\phi_1+\delta_1-\delta_{12}-\varphi_2) - Y_o \frac{V_2}{\lambda} \text{ Sin } \phi_1 = 0 \;...(2.30)$$

Neglecting resistance $\varphi_1 = \varphi_2 = 90^o$ we get

$$E_1Y_1 \text{ Cos } (90-\phi_1-\delta_1) - E_2Y_2 \text{ Cos } (90-\phi_1-\delta_1+\delta_{12}) - Y_o\frac{V_2}{\lambda} \text{ Cos } \phi_1 = KId$$

$$E_2Y_2 \text{ Sin } (\delta_{12}-\phi_1+\delta_1) + E_1Y_1 \text{ Sin}(\phi_1 + \delta_1 \;) - Y_o\frac{V_2}{\lambda} \text{ Cos } \phi_1 = K.Id..(2.31)$$

and

$$-E_1Y_1 \text{ Sin}(90-\phi_1-\delta_1) + E_2Y_2 \text{ Sin}(90+\delta_{12}-\delta_1-\phi_1) - Y_o\frac{V_2}{\lambda} \text{ Sin } \phi_1 = 0.$$

$$E_2Y_2 \text{ Cos } (\delta_{12}-\phi_1-\delta_1) + E_1Y_1 \text{ Cos } (\phi_1 + \delta_1) - Y_o\frac{V_2}{\lambda} \;\; \text{Sin } \phi_1 = 0 \;..(2.32)$$

Relation between displacement factor (ϕ_1) and angle of overlap remains same as expressed by equation 2.15

2.4.2. ANALYSIS FOR RECEIVING END

Considering the equivalent circuits of figure 2.4(b).

Taking Ids(=K Id) as reference the vector relations are shown in Figure

Let $Z_{2r} = |Z_{2r}| \angle \varphi_1$ $Y_{2r} = |Y_{2r}| \angle -\varphi_1$
$Z_2 = |Z_2| \angle \varphi_2$ $Y_2 = |Y_2| \angle -\varphi_2$
$Z_r = |Z_r| \angle -\phi_r$ $Y_r = |Z_r| \angle \phi_r$

} As represented in Figure.

$$\lambda = \frac{K_1 \text{ Cos } \alpha}{K_2 \text{ Cos } \beta}$$

$$\dot{V}_2 = |V_2| \underline{/-\phi_r}$$

$$\dot{E}_1 = |E_1| \underline{/-\phi_r + \delta_2}$$

$$\dot{E}_2 = |E_2| \underline{/-\phi_r + \delta_2 - \delta_{12}}$$

Writing current equation at the node

$$\lambda E_1 Y_r + KId + E_1 Y_{2r} = E_2 Y_2 \qquad \ldots(2.33)$$

$$KId = E_2 Y_2 - E_1 Y_{2r} - \lambda E_1 Y_r$$

$$KId = E_2 Y_2 \underline{/\delta_2 - \phi_r - \delta_{12} - \varphi_2} - E_1 Y_{2r} \underline{/-\delta_2 - \phi_r - \varphi_1} - \lambda E_1 Y_r \underline{/-\phi_r} \qquad (2.34)$$

Direct current has no imaginary part, therefore the imaginary part of eqn. 2.34 is equated to zero.

$$KId = E_2 Y_2 \text{ Cos } (\delta_2 - \phi_r - \delta_{12} - \varphi_2) - E_1 Y_{2r} \text{ Cos} (\delta_2 - \phi_r - \varphi_1) - \lambda E_1 Y_r \text{ Cos } \phi_r \qquad (2.35)$$

Neglecting resistance of transmission line

$$\varphi_1 = \varphi_2 = 90^\circ$$

Substituting in eqn. 2.35

$$KId = E_2 Y_2 \text{ Cos } (90 + \delta_{12} - \phi_r - \delta_2) - E_1 Y_1 \text{ Cos} (90 + \phi_r - \delta_2) - \lambda E_1 Y_r \text{ Cos } \phi_r$$

$$KId = E_1 Y_1 \text{ Sin } (\phi_r - \delta_2) - E_2 Y_2 \text{ Sin } (\delta_{12} + \phi_r - \delta_2) - \lambda E_1 Y_r \text{ Cos } \phi_r \qquad (2.36)$$

Equating Imaginary part of equation 2.34 to zero.

$$0 = -E_2 Y_2 \text{ Sin } (90 + \delta_{12} - \phi_r - \delta_2) + E_1 Y_1 \text{ Sin} (90 + \phi_r - \delta_2) + \lambda E_1 Y_r \text{ Sin } \phi_r$$

$$0 = -E_2 Y_2 \text{ Cos } (\delta_{12} + \phi_r - \delta_2) + E_1 Y_1 \text{ Cos } (\phi_r - \delta_2) + \lambda E_1 Y_1 \text{ Sin } \phi_r \qquad (2.37)$$

The expressions for ϕ_2, current, firing angle and remain same as expressed by equations 2.3, 2.17 and 2.22.

On the basis of equations given in this chapter, it is possible to analyse a combined system.

CHAPTER - 3

CHAPTER-3

REACTIVE POWER REQUIREMENTS

3.1. NEED OF REACTIVE POWER

Converter can be arranged to supply the power in either direction by controlling grid action.(9) A converter may be operated as rectifier or as invertor. Irrespective of the direction of power flow, the d.c. side of the converter can supply only active power, it cannot supply reactive power. In other words converter is a machine which consumes the reactive power and therefore the stable operation is impossible without the supply thereof.(6,7,8)

When a converter is operating as a rectifier, it is considered as a load which has inductance due to leakage reactance of transformer and also due to the delay associated with grid control, which is required to control the output voltage. Therefore, the rectifier operates at a lagging power factor, and requires reactive power supply. This reactive power is supplied in this case, together with active power, by the a.c. system itself.

In case of invertor, where power flow is from d.c. line to a.c. system, it is treated as a generator which can supply only active power, on the other hand, it needs some reactive power to meet the reactive power requirements of invertor transformer reactance and advance firing angle. Thus an invertor can be treated as operating at a leading power factor. In this case the a.c. system accepts the active power from invertor but it must itself supply the reactive power, or some other means should be provided so that invertor reactive power demand is met.

3.2. GENERAL EXPRESSION FOR REACTIVE POWER[9]

The ratio of alternating to direct current[5] as given in Chapter 2 is

$$\frac{I}{I_d} = \frac{\sqrt{6}}{\pi} \cdot \frac{\sqrt{\left[\cos 2\beta - \cos 2(\beta-\gamma_r)\right]^2 + \left[2\gamma_r + \sin 2(\beta-\gamma_r) - \sin 2\beta\right]^2}}{4\left\{\cos(\beta-\gamma_r) - \cos\beta\right\}} \qquad \ldots 3.1$$

which can be approximated as

$$I = \frac{\sqrt{6}}{\pi} I_d \qquad \ldots(3.2)$$

I = Alternating Current from inverter

Direct output voltage developed by the inverter is

$$V_d = V_o \left[\frac{\cos\beta + \cos\delta}{2}\right] \qquad \ldots(3.3)$$

where $V_o = \frac{3\sqrt{2}}{\pi} \cdot E$ = no load direct voltage.

Equating a.c. and d.c. powers

$$\frac{3\sqrt{2}}{\pi} E \left[\frac{\cos\beta + \cos\delta}{2}\right] I_d = \sqrt{3}\, EI \cos\phi \qquad \ldots(3.4)$$

$$= \sqrt{3}\, E \frac{\sqrt{6}}{\pi} I_d \cos\phi$$

Thus

$$\cos\phi = \left[\frac{\cos\beta + \cos\delta}{2}\right] \qquad \ldots(3.5)$$

Active component of the alternating current is given by

$$I(a) = I \left[\frac{\cos\beta + \cos\delta}{2}\right] \qquad \ldots(3.6)$$

A.C. Apparent power is given by

$$P = \sqrt{3}\, EI = V_o I_d \qquad \ldots(3.7)$$

and active power (which is d.c. power also)

$$P(a) = V_o I_d \left[\frac{\cos\beta + \cos\delta}{2}\right] \qquad \ldots(3.8)$$

reactive power can now be found from[9]

$$P(r) = \sqrt{P^2 - P(a)^2} \qquad \ldots(3.9)$$

or

$$P(r) = V_o I_d \sin\phi \qquad \ldots(3.10)$$

where

$$\text{Sin}\,\phi = \text{Sin}\left\{\cos^{-1}\left[\frac{\text{Cos}\,\beta + \text{Cos}\,\delta}{2}\right]\right\} \quad ...(3.11)$$

Direct current of inverter[1,2] is

$$I_d = \frac{E}{\sqrt{2}\,\omega L}\left[\text{Cos}\,\delta - \text{Cos}\,\beta\right] \quad ...(3.13)$$

Substituting the value of Id from 3.13 in 3.10, we get

$$P_r = \frac{3\sqrt{2}}{\pi}\cdot E\;\frac{E}{\sqrt{2}\,\omega L}\left[\text{Cos}\,\delta - \text{Cos}\,\beta\right]\text{Sin}\,\phi \quad (3.14)$$

$$= \frac{3E^2}{\pi\,\omega L}\left[\text{Cos}\,\delta - \text{Cos}\,\beta\right]\cdot\text{Sin}\left[\cos^{-1}\frac{\cos\delta + \cos\beta}{2}\right] \quad (3.15)$$

Expression 3.15 is important because it relates the reactive power with other operating parameters of the system.

Now using equation 3.14, we have

$$\text{Cos}\,\phi = \frac{\text{Cos}\,\delta + \text{Cos}\,\beta}{2}$$

$$\text{or} \quad \text{Cos}(\beta) = 2\cos\phi - \cos\delta \quad (3.16)$$

Substituting 3.16 in (3.14) we get

$$P_r = \frac{3E^2}{\pi\,\omega L}\times 2\left[\text{Cos}\,\delta - \text{Cos}\,\phi\right]\text{Sin}\,\phi \quad (3.17)$$

Equation 3.17 gives a simplified expression for reactive power.

3.3. REACTIVE POWER FOR VARIOUS TYPES OF LOADS

Now let us consider the variation of reactive power with different types of load.

Let load power be (P + jQ), under following assumptions

E_L = Load voltage(constant)

ϕ = Power factor at inverter end.

γ

ϕ_L = Load power factor

R = Transformer resistance (neglected).

X = Transformer reactance

Let the load be situated at the secondary of the inverter transformer such that the reactance and resistance of transmission line may be neglected.

Vector diagram for this condition is shown in figure 3.1. From vector diagram, the power factor angle at the inverter end is given by

$$\tan \phi = \frac{E_L \sin \phi_L + I.X}{E_L \cos \phi_L + I.R.} \qquad ..(3.18)$$

neglecting resistance of transformer, R = 0

and assuming transformer leakage reactance has a finite value

$$\tan \phi = \frac{E_L \sin \phi_L + IX}{E_L \cos \phi_L} \qquad ..(3.19)$$

Load power = P + jQ

$\therefore \quad \phi_L = \tan^{-1}\left(\frac{Q}{P}\right)$

Where:
P=Active component of power
Q= Reactive component of power ...(3.20)

<u>Case: 1</u>

(a) Resistive Load i.e. Q = 0

Substituting $\sin \phi_L = 0$

$\cos \phi_L = 1$

Equation 3.19 becomes

$$\tan \phi = \frac{I.X}{E_L} \qquad .....(3.21)$$

and $E = E_L + j\, I.X.$ .....(3.22)

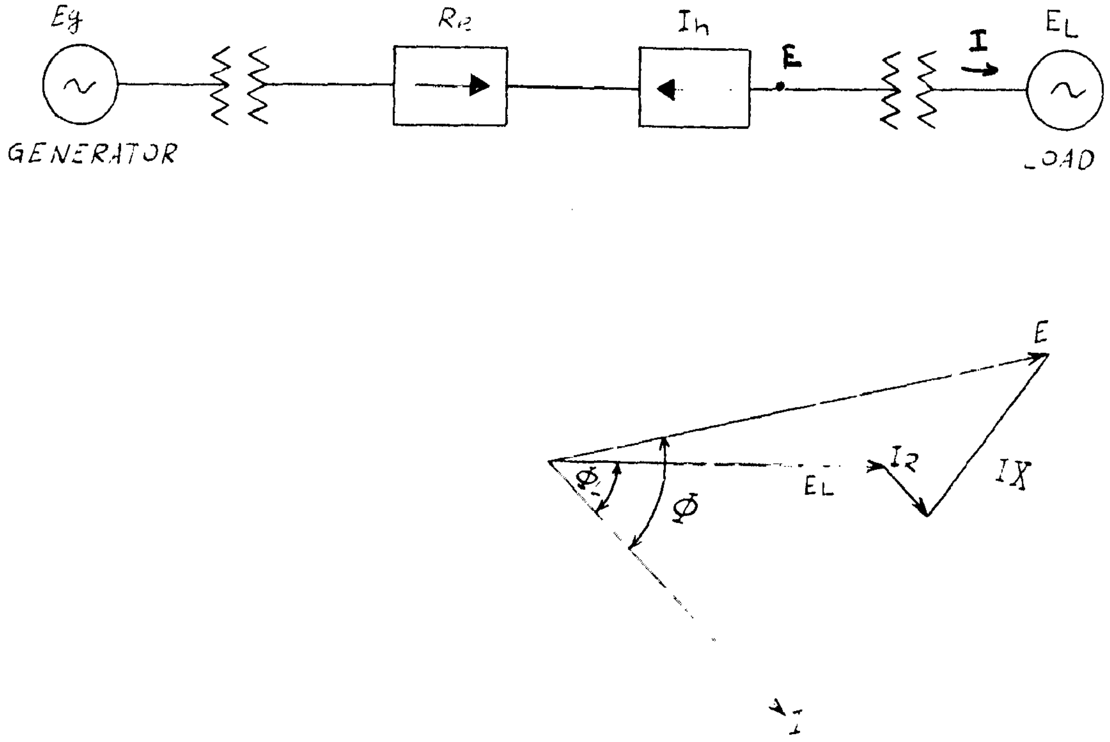


FIGURE 3·1

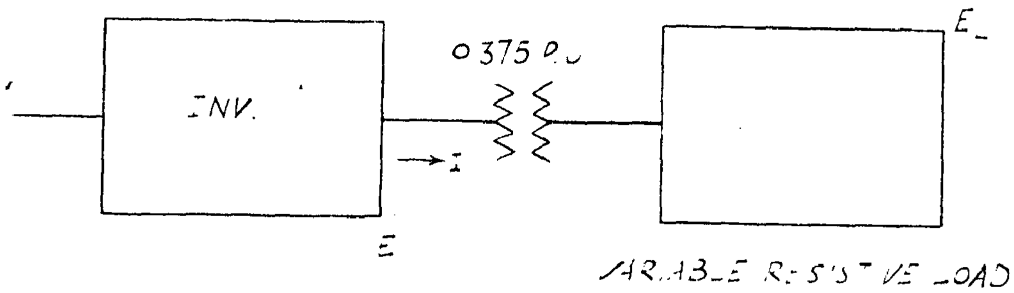


FIGURE 3·2

The reactance X of the transformer remains constant so long as supply frequency is constant. This is true for all practical purposes. Quantity $\frac{I.X}{E_L}$ represents percentage reactance of the transformer, therefore, the invertor displacement angle ϕ and hence overlap angle, is related to the percentage reactance of the transformer.

EXAMPLE:

For the system shown in Fig. 3.2 we will calculate the reactive power requirements for a resistive load

Case 1, Q = 0, i.e. load reactive power = 0

Let E_L = 1.0 p.u.

X = 0.375 p.u. per phase

= 10°

$E = E_L + jI.X.$ ....from Eqn. 3.22

$$\tan \phi = \frac{E_L \sin \phi_L + I.X}{E_L \cos \phi_L} = \frac{I.X}{E_L} \quad \text{...from eqn.(3.19)}$$

Using equation (3.17)

$$P_r = \frac{6E^2}{\pi \omega L} (\cos \delta - \cos \phi) \sin \phi \quad \text{..(3.17)}$$

Substituting the values in (3.17)

$$P_r = 5.1\, E^2 (0.985 - \cos \phi) \sin \phi$$

For different values of current, ϕ and E are calculated from eqn. 3.19 and 3.22 and then P_r is found corresponding to these values. Calculated results are tabulated in Table 1. The results have been plotted in graph 3.3(α).

Case 2.

Reactive Load - Now the variation of reactive power with load power factor will be considered .

The power factor at inverter end is given by equation 3.18

$$\tan\phi = \frac{E_L \sin \phi_L + I.X}{E_L \cos \phi_L} \qquad \ldots\ldots 3.18$$

$$\tan\phi_L = \frac{Q}{P}$$

$$\therefore \phi_L = \tan^{-1}\left(\frac{Q}{P}\right) \qquad \ldots\ldots 3.20$$

Substituting value of ϕ_L in eqn. 3.18, we get

$$\tan\phi = \frac{E_L \sin\left\{\tan^{-1}\left(\frac{Q}{P}\right)\right\} + I.X.}{E_L \cos\left[\tan^{-1}\left(\frac{Q}{P}\right)\right]} \qquad \ldots 3.23$$

The reactive power required is given by eqn. 3.17

$$P_r = \frac{3\times 2\ E^2}{\pi\omega L}(\cos\delta - \cos\phi)\sin\phi$$

<u>EXAMPLE 2.b</u>

Taking the system of fig. 3.2. with same parameters.

In this case we will calculate reactive power for different load power factor and for a particular value of current.

For different ratio of $\frac{Q}{P}$, ϕ is calculated from 3.23.

Substituting these values of ϕ in equation 3.17 reactive power is calculated. In this case reactive power has been calculated for two values of current I = 1.0 p.u. and I = 2.0 p.u.

Calculated results are tabulated in Table 2(a) and 2(b) Fig.... shows the curve showing the variation of reactive power demand of inverter with ratio $\left(\frac{Q}{P}\right)$ for load.

<u>3.4. CONCLUSION</u>

Graphs showing variation of reactive power for different types of load conditions i.e. variable resistive and reactive loads

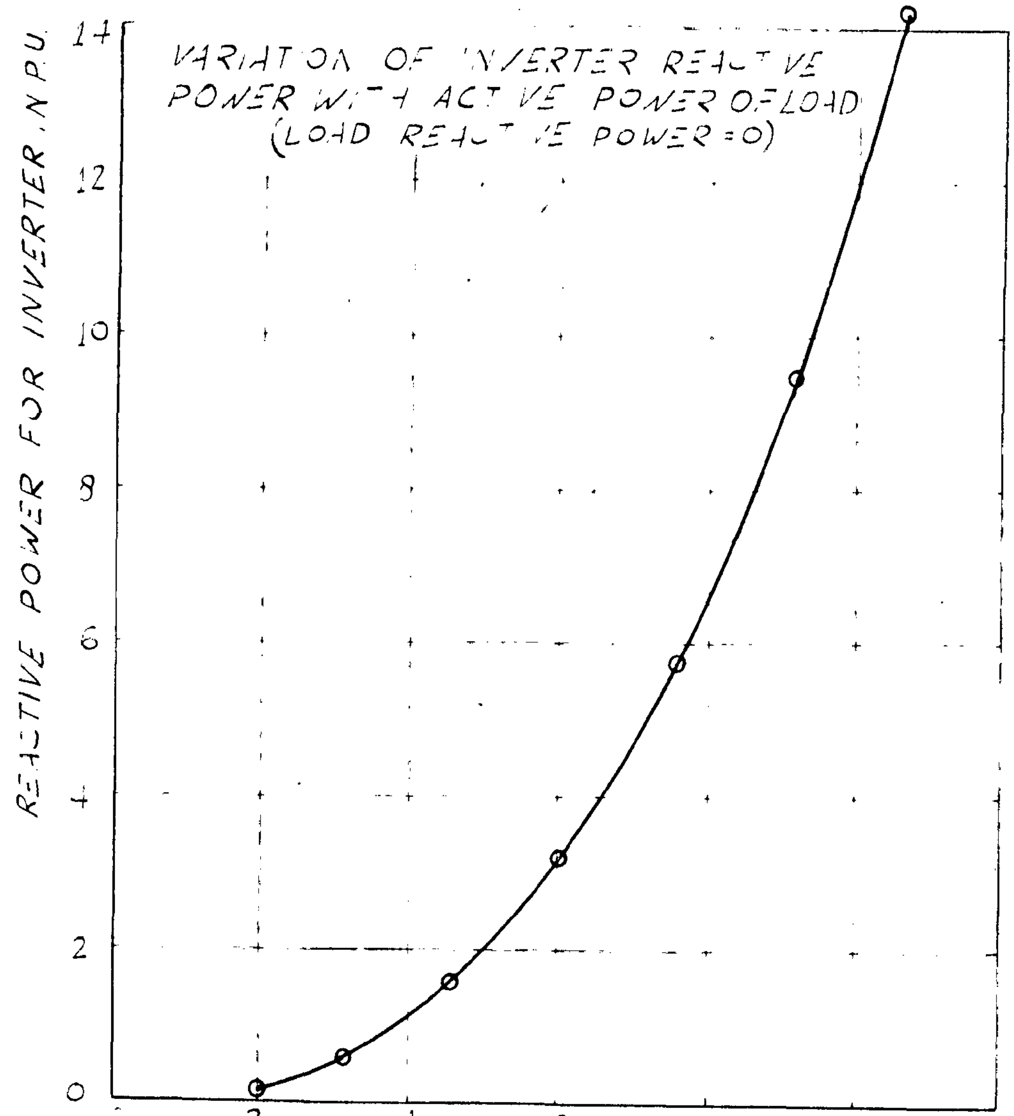

VARIATION OF INVERTER REACTIVE POWER WITH ACTIVE POWER OF LOAD (LOAD REACTIVE POWER = 0)
REACTIVE POWER FOR INVERTER IN P.U.
ACTIVE POWER OF LOAD P.U.
0
2
4
6
8
10
12
14

FIGURE 3.3(a)

The power factor at inverter end is given by equation 3.18

$$\tan \phi = \frac{E_L \sin \phi_L + I.X}{E_L \cos \phi_L} \qquad \ldots\ldots 3.18$$

$$\left.\begin{aligned} \tan \phi_L &= \frac{Q}{P} \\ \therefore \phi_L &= \tan^{-1}\left(\frac{Q}{P}\right) \end{aligned}\right\} \qquad \ldots\ldots 3.20$$

Substituting value of ϕ_L in eqn. 3.18, we get

$$\tan \phi = \frac{E_L \sin \left\{\tan^{-1}\left(\frac{Q}{P}\right)\right\} + I.X.}{E_L \cos \left[\tan^{-1}\left(\frac{Q}{P}\right)\right]} \qquad \ldots 3.23$$

The reactive power required is given by eqn. 3.17

$$P_r = \frac{3\times 2 \; E^2}{\pi \omega L} (\cos\delta - \cos\phi) \sin\phi$$

EXAMPLE 2.b

Taking the system of fig. 3.2. with same parameters.

In this case we will calculate reactive power for different load power factor and for a particular value of current.

For different ratio of $\frac{Q}{P}$, ϕ is calculated from 3.23.

Substituting these values of ϕ in equation 3.17 reactive power is calculated. In this case reactive power has been calculated for two values of current I = 1.0 p.u. and I = 2.0 p.u.

Calculated results are tabulated in Table 2(a) and 2(b) Fig.... shows the curve showing the variation of reactive power demand of inverter with ratio $\left(\frac{Q}{P}\right)$ for load.

3.4. CONCLUSION

Graphs showing variation of reactive power for different types of load conditions i.e. variable resistive and reactive loads

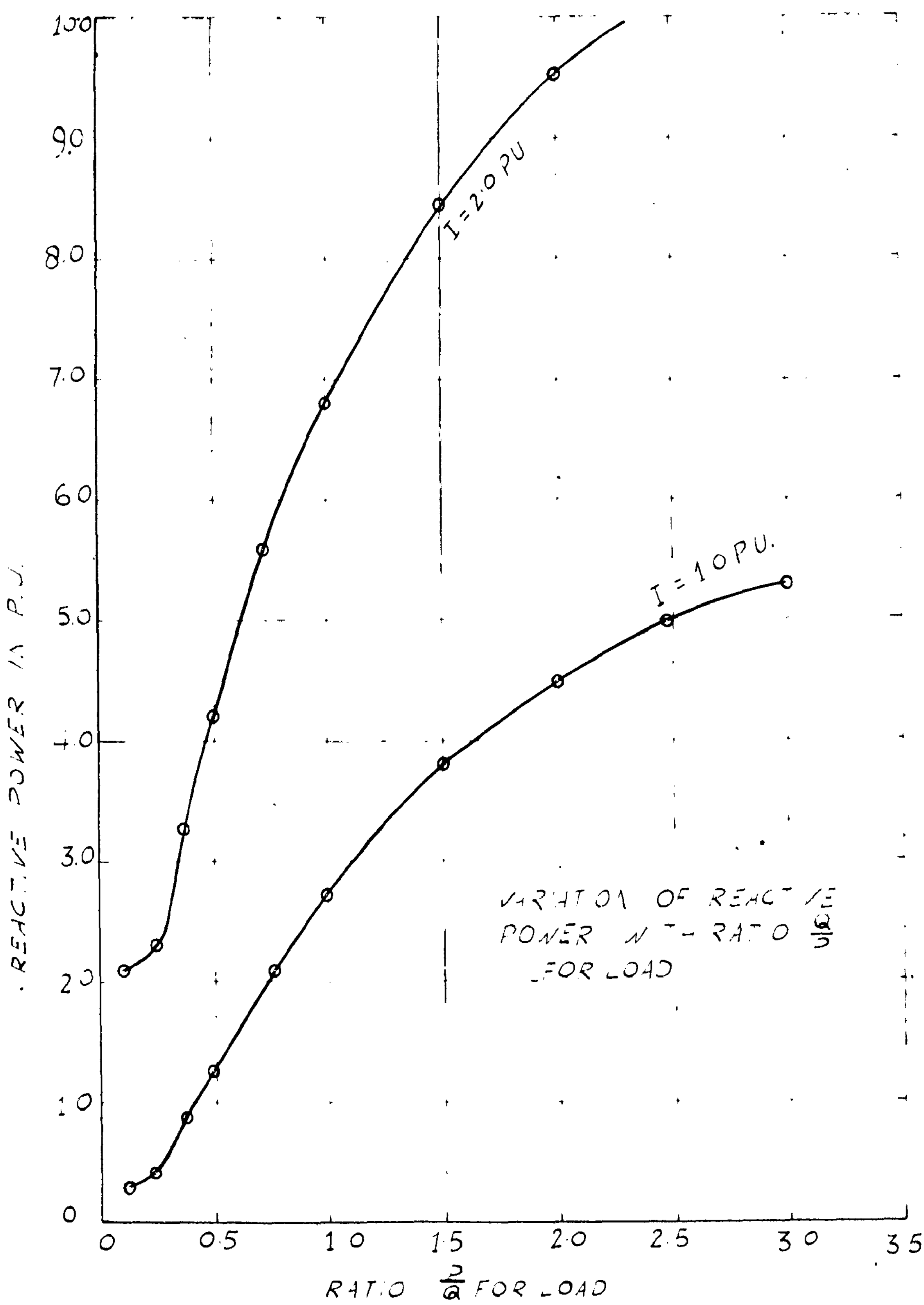

REACTIVE POWER IN P.U.
I = 2.0 PU
I = 1.0 PU
VARIATION OF REACTIVE POWER WITH RATIO P/Q FOR LOAD
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
RATIO P/Q FOR LOAD

FIGURE 3.4

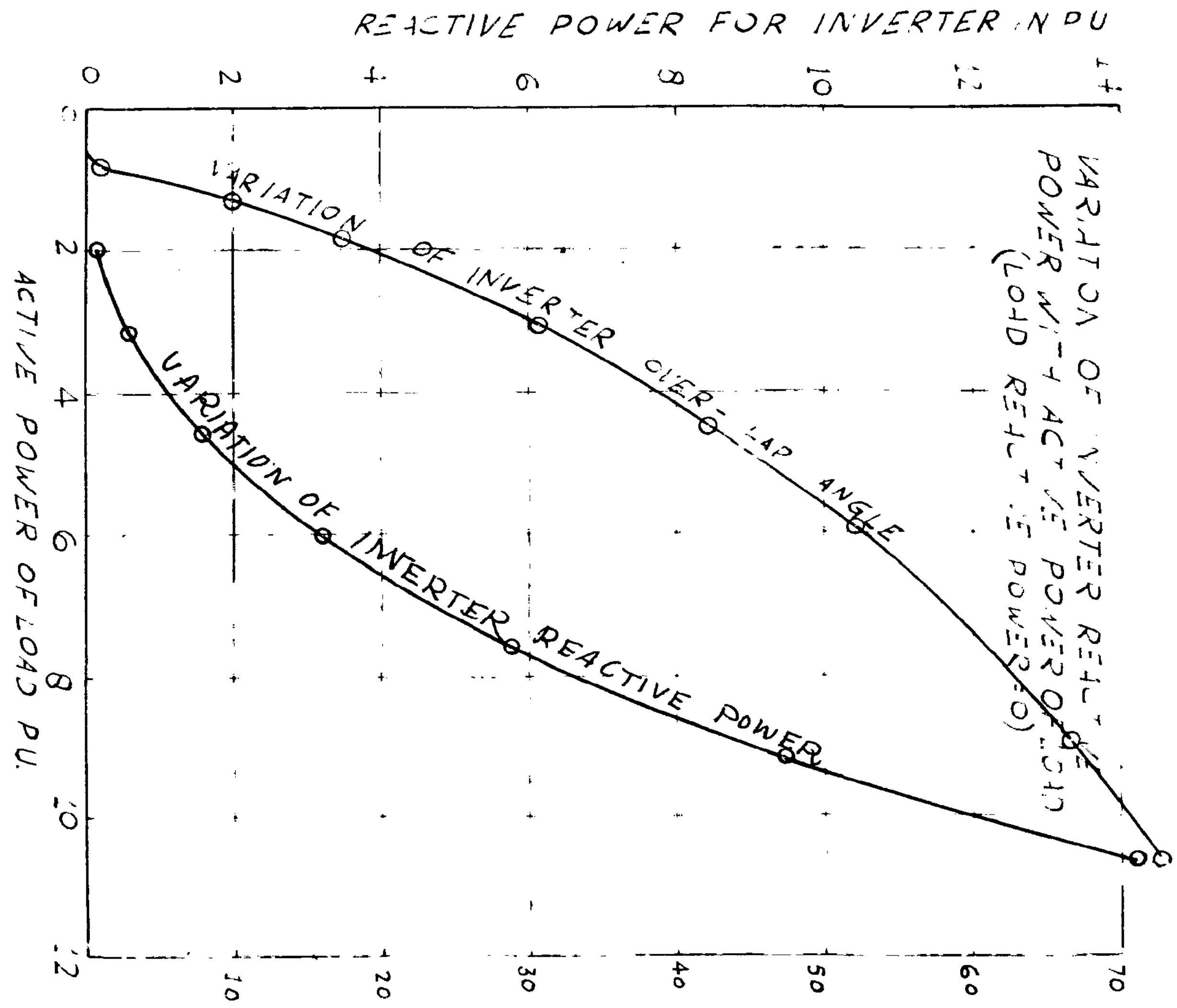

REACTIVE POWER FOR INVERTER IN PU
ACTIVE POWER OF LOAD PU.
VARIATION OF INVERTER REACTIVE POWER
VARIATION OF INVERTER OVER-LAP ANGLE
0
2
4
6
8
10
12
14
10
20
30
40
50
60
70

FIGURE 3.3(b)

lead to the conclusion that inverter needs a considerable amount of reactive power for its operation. Figure 3.3.(a) shows the variation of reactive power required for inversion (when load reactive power is zero) as a function of active power delivered by inverter. It is seen that under normal range of operation, in this case upto 5 p.u., load, the reactive power demand is not much, it is only 40% of the active load. As the load increases, reactive power demand also increases, and beyond active load of 90 p.u. the curve becomes more steep and it may not be economical to supply reactive power at such a high rate.

Inverter, however, may not be operated at such a high load and hence we can say that it is not difficult to meet the reactive power demand under normal range of operation.

Further more, it is seen from fig.3.3.(a) that when load is purely resistive, the reactive power required for inversion is not constant, it increases with the active power consumed by the load. This is because of the fact that when increased current is drawn from inverter, its overlap angle increases, which is responsible for this increase in reactive power.(graph 3.3 b)

In figure 3.4. variation of reactive power demand for inverter load power factor is shown. It is seen that a load at poor power factor will require more reactive power because of its reactance will increase the overlap angle of inverter. High power factor reduces the demand for reactive power for inversion and hence resistive loads can be more conveniently supplied by inverter. Graph is plotted for two values of load currents (for 1.0 p.u. and 2 p.u.) to show that high load current leads to larger consumption of reactive power.

In general, we can conclude that in all cases, the reactive power demand is not high at initial stages. But, it increases rapidly as the load is increased or power factor falls. Therefore, trouble may come in operation if precautionary measures are not taken to meet this reactive power demand.

TABLE - 1

VARIATION OF REACTIVE POWER [illegible] FOR INVERTER WITH ACTIVE POWER OF LOAD, ($Q_L = 0$)

I (Load Current) p.u.	0.5	0.75	1.0	1.5	2.0	2.5	3.0	3.5	4
tan Ø	.1875	.281	.375	.563	.75	.938	1.125	1.314	1.5
Cos Ø	.983	.9626	.936	.871	.800	.729	.6678	.606	.5533
(.985-Cos Ø)	.002	.023	.049	.114	.185	.256	.317	.379	.432
Sin Ø	.184	.27	.352	.491	.600	.684	.744	.795	.833
E	1.05	1.11	1.19	1.4	1.64	1.91	2.19	2.48	2.78
E^2	1.10	1.233	1.42	1.947	2.68	3.63	4.77	6.156	7.74
P (reactive) p.u.	.0206	.039	.125	.556	1.52	3.24	5.72	9.46	14.20
P (active) p.u.	.892	1.39	1.93	3.16	4.56	6.04	7.6	9.15	10.66

$E = E_L + j\, I.X$

TABLE- 1 (a)

VARIATION OF OVERLAP ANGLE WITH LOAD POWER

(Graph 3.3.b)

$\cos\phi = \frac{1}{2}[\cos\delta + \cos(\delta+r)]$, Using table 1, r is calculated for various values of loads.

Power p.u.	0.892	1.39	1.93	3.16	4.56	6.04	7.6	9.15	10.66	
Overlap Angle 'r' degrees	1.2°	10°	17.5°	30.8°	42°	52.4°	59.1	66.3°	73°	

TABLE -2(a)

VARIATION OF REACTIVE POWER DEMAND OF INVERTER WITH RATIO $\frac{Q}{P}$ OF LOAD(I = 1.0 PER UNIT)

$\tan \phi_L = \frac{Q}{P}$	0.125	.25	.375	.50	.75	1.0	1.5	2.0	2.5	3.0
Tan ϕ	.501	.534	.778	.92	1.22	.1535	2.17	2.84	3.52	4.2
Cos ϕ	.891	.882	.789	.735	.619	.548	.414	.332	.274	.231
.985-Cos ϕ =(A)	.94	.103	.196	.250	.366	.437	.571	.653	.711	.754
Sin ϕ =(B)	.455	.47	.615	.676	.785	.836	.911	.943	.916	.973
Pr=7.25(A)(B) for I=1.0 p.u.	0.31	.351	.873	1.228	2.09	2.65	3.78	4.46	4.73	5.32

TABLE -2(b)

VARIATION OF REACTIVE POWER DEMAND OF INVERTER WITH RATIO $\left(\frac{Q}{P}\right)$ FOR LOAD (I = 2.0 PER UNIT)

Tan $\theta_L = \frac{Q}{P}$	.125	.25	.375	.5	.75	1.0	1.5	2.0	2.5	3
Tan ø	.80	.92	1.175	1.34	1.69	2.06	2.86	3.68	4.5	5.4
Cos ø	.75	.735	.665	.60	.51	.432	.330	.262	.216	.184
.985-Cosø	.235	.250	.320	.385	.475	.553	.655	.723	.769	.801
Sin ø	.66	.678	.745	.80	.86	.90	.944	.965	.976	.983
Pr=8 in p.u.	2.12	2.32	3.26	4.2	5.57	6.8	8.45	9.51	10.25	10.72

CHAPTER - 4

CHAPTER-4

EFFECT OF SYSTEM PARAMETERS ON REACTIVE POWER & SOURCES TO MEET REACTIVE POWER DEMAND

4.1. INTRODUCTION

Reactive power required by the invertor is given by eqn. 3.15 of Chapter 3

$$Pr = \frac{3E_2^2}{\pi \omega L_2} \left[\cos \delta - \cos(\delta + \gamma_r) \right] \sin \left[\cos^{-1} \cdot \frac{\cos \delta + \cos(\delta + \gamma_r)}{2} \right]$$

It can be seen that reactive power Pr depends mainly on the overlap angle γ_r of invertor. This angle is responsible for variation of reactive power demand for inversion. Therefore, it may be desirable to investigate the effect of various system parameter on this angle.

4.2. VARIATION OF OVERLAP ANGLE[1,2,6,28]

Overlap angles depends primarily on the following factors:

I) Load current

II) Voltage at invertor transformer secondary.

III) Reactance of Transformer

IV) Load power factor,

V) A.C. System Faults.

I) LOAD CURRENT - Overlap angle is related with direct current in accordance with the following equation

$$Id = \frac{E_2}{\sqrt{2}\, \omega L_2} \left[\cos \delta - \cos(\delta + \gamma_r) \right]$$

It is observed that with increasing current, overlap angle increases, therefore, for high power transmission this angle has to increase. Hence more and more reactive power is required to maintain stable operation of inverter.

II) VOLTAGE AT INVERTER TRANSFORMER SECONDARY:

Following relation stands valid for direct and alternative voltages.

$$Ed = \frac{3\sqrt{2}}{\pi} E2 \left[\frac{\cos\delta + \cos(\delta+\gamma_r)}{2}\right]$$

For constant direct voltage at inverter end, a reduced transformer secondary voltage will have tendency to increase overlap angle. Therefore giving rise to increased consumption of reactive power.

III) REACTANCE(LEAKAGE) OF TRANSFORMER

The inductance of transformer does not permit the current in a particular phase at the beginning of commutation to reach the full value Id . It takes certain time for current to reach upto this value. This is represented by a time lag, and similarly at the end of commutation, the current of this phase does not suddenly drops to zero. The angle associated with this lag(i.e. when the current is increasing to full value and falling to zero), is known as overlap angle and is represented by γ_r. This overlap angle increases with increase in transformer reactance as given by the following equation:-

$$\omega L_2 = \frac{E2}{\sqrt{2}\, Id} \left[\cos\delta - \cos(\delta+\gamma_r)\right]$$

Graph 4.1. shows the variation of reactive power with percentage leakage reactance of transformer.

VARIATION OF REACTIVE POWER WITH TRANSFORMER LEAKAGE REACTANCE.

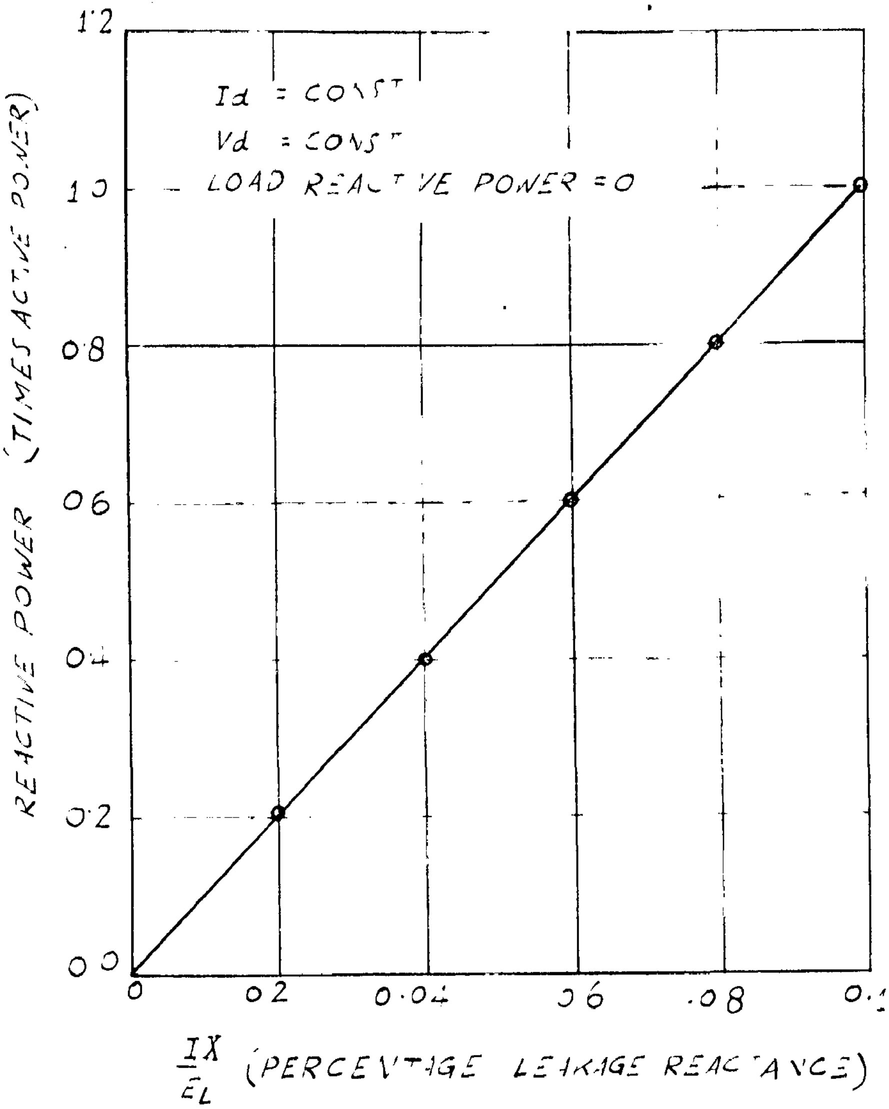


FIGURE 4·1

The transformer is needed not only from voltage transformation, but for isolation purpose also. Thus, even if proper voltage for valve is available, a one to one ratio transformer will be required to isolate d.c. system from a.c. system. The transformer and associated inductance is therefore unavoidable.

IV) LOAD POWER FACTOR:

Load power factor also contributes towards the reactive power demand. It is seen from equation 3.18 of Chapter 3, that

$$\tan \phi = \frac{E_L \sin \phi_L + IX}{E_L \cos \phi_L + AR}$$

It is obvious that a low power factor tends to increase angle ϕ, i.e. effect is to increase the overlap angle and hence increased demand for reactive power.

V) A.C. SYSTEM FAULTS:[1,10,16]

The faults on a.c. system, in general cause either reduction of voltage or collapse of voltage, considering a three phase fault at the a.c. side of invertor, the voltage available for commutation will be decreased. This will be followed by increase of overlap angle and thus more demand of reactive power. Against system faults, it is desirable to have an effective control of static capacitor to meet the system reactive power demand.

A.3. MINIMUM ANGLE OF VALVE FIRING:[25,16]

It has been stated earlier that for every valve, there is a certain time in which the grid recovers its controlling ability. The angle associated with this time is known as deionisation angle and represented by δ. Therefore advance firing angle β is made up of two parts $\beta = \delta + \gamma_r$

for successful commutation it is essential that angle β is always secured at least equal to δ .

During normal operation, the inverters operate with as small β as possible, thereby reducing the need of reactive power.

4.4. SAFETY OF INVERTER OPERATION: [1,2,9,11,13]

As stated in preceding paragraph, minimum angle δ is required to secure successful commutation. This angle is about 10^{o} but as a matter of fact, it differs from valve to valve. In the case of faults or disturbances, when current and voltage of the system are liable to change, there is a possibility that γ_r will increase, thereby reducing δ , therefore this results in a fault known as commutation failure. In all the systems where constant β control is practiced, the reduction of receiving end voltage will result in a commutation failure, if sufficient margin on firing angle β is not provided.[14]

It becomes clear now that safety of inverter operation is achieved by providing a larger β , and in fact larger the firing angle, greater is this safety. At the same time it may also be noted that greater value of β , will require a larger amount of reactive power. We can conclude, that safety of inverter operation increases at the cost of reactive power.

4.5. FORCED COMMUTATION:

Investigations on reactive power have lead to the possibility of reducing or even eliminating reactive power. It is rather a "preventive" method and is achieved by "forced commutation" that is by means of which commutation is achieved even after the 'voltage zero' on the a.c. side, thus not only making it possible for inverter not to consume reactive power but even to supply it to the system load requirements.

4.6. REDUCTION OF REACTIVE POWER: [9]

Dr. N.G.Hingorani, of Manchester College of Science and Technology, has suggested a method to reduce reactive power demand. Usual practice is to connect static capacitors or filters on the primary side (i.e. line side) of the inverter transformer or alternatively a tertiary winding is provided, specially for static capacitors. If instead of line side, these filters or static capacitors are connected on valve side(i.e. on secondary side of the inverter transformer), the capacitor would assist commutation, resulting in a reduced overlap angle and thus allowing the inverter to operate at an improved power factor. It may, however, be mentioned here that efforts to reduce reactive power are being done since as early as 1942.

reactive power is given by

$$P_r = V_{0}I_{d}\sin\phi$$

$$\text{where } \cos\phi = \frac{[\cos\delta + \cos(\delta+\gamma_r)]}{2}$$

by reducing γ_r saving in reactive power results, use of capacitors and filters is helpful in reducing overlap angle. Methods to reduce reactive power demand are still in experimental stage hence their discussion is omitted.

4.7. SUPPLY OF REACTIVE POWER [1,9,11]

4.7.1. Inverter needs considerable amount of reactive power to be supplied for stable operation. This reactive power is small during normal operation conditions but under transient conditions it becomes very high. The apparatus supplying such a great amount

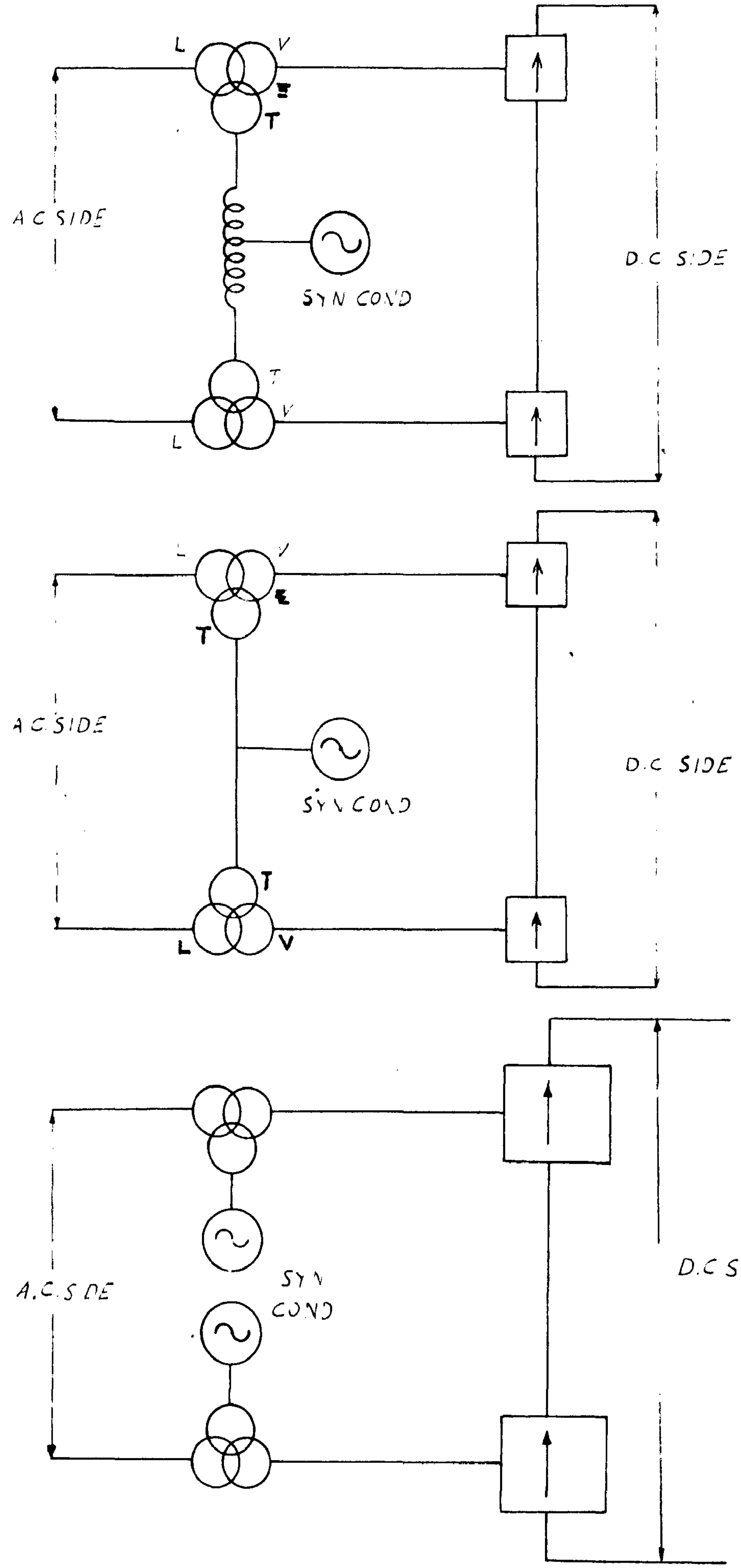


FIGURE 4.2 - ARRANGEMENTS OF SYNCHRONOUS CONDENSER
L = LINE WINDING

of reactive power, other than a.c. generator, synchronous condenser will come to mind. However, recently, as the apparatus supplying reactive power, static condenser(Bank of static capacitor) has come into picture.

Reactive power in a simple d.c. system can also be supplied by the exciting a.c. system at the inverter end but in the case where the large blocks of power are to be transferred, exciting a.c. system may not be adequate, extra measures to supply reactive power are to be taken therefore. Synchronous condenser and static capacitor may serve this purpose, practically speaking, static capacitors are used for small loading of d.c. lines but where the converter is rated for large power, synchronous condensers are provided. In practice, synchronous condensers are connected to the tertiary winding of the converter transformer through a decoupling reactor. The main function of decoupling reactor is to reduce the mutual interaction of the two converter transformer. Several arrangements of connecting synchronous condenser are shown in figure 4.2.

Choice between synchronous condensers and static capacitors may depend on many economical & technical factors, at one place synchronous condenser may be more advantageous while static capacitor at the other place. Sometimes it may be more feasible economically and technically, to use a combination of the both. Some advantages and disadvantages of each of them are listed below:

4.7.2. SYNCHRONOUS CONDENSER

1. Synchronous condensers have better characteristics from regulation point of view.
2. In the event when voltage falls due to load increase, the regulating arrangement will provide an increase in the KV Ar and prevent the system from running down.
3. Losses in synchronous condensers are more than in the case of static capacitors.

4.7.3. BANK OF STATIC CAPACITORS

1. Static capacitors are cheaper, have small losses, and low cost of operation.
2. Because of reduced overlap angle, reactive power demand is reduced so system is operated at high power factor and better utilisation of installed capacity is achieved.
3. In the case of large capacity of static capacitor, the wave form of voltage is improved.
4. Investigations are being done on the possibility to run an inverter without any dynamic source of alternating voltage (i.e. synchronous condenser or auxilliary power system). In such a case, the system is run at the natural frequency determined by the capacitance provided and parameters of the system. Such system of course is complicated and not yet practicable.
5. One added advantage of static capacitor is that because of their large time constant, under fault or sudden load change conditions in the a.c. systems

the static capacitor can sustain the voltage in the period immediately subsequent to disturbance. This will not allow sudden voltage change. Instead it will allow the valves to adjust their firing angle with greater facility and reduce the possibility of commutation failure.

In practical schemes KASHIRA-MOSCOW TRANSMISSION uses only static capacitors to supply reactive power.

Originally in Donbass - Stalingrad Transmission, it was proposed to install synchronous condensor and static capacitor to share the KVAr required in ratio 3:1, connected to tertiary winding of main transformer. But now it has been decided to use only static capacitors. This new arrangement has reduced the KVAr consumption to 400 KVAr against 450 KVAr for a load of 750 KW.

CHAPTER - 5

CHAPTER 5

POWER ANGLE CHARACTERISTICS

5.1. INTRODUCTION

The power transmitted over a d.c. line is given by[13]

$$P_{d.c.} = \frac{(E_{d1} - E_{d2})\, E_{d1}}{R} \qquad \text{....5.1.}$$

Equation 5.1. shows that the transmitted power is proportional to the difference of two d.c. voltages at the sending and receiving end. Thus no power can be transmitted over a d.c. line if both the terminal voltages are maintained equal. In a.c. transmission, the power is transmitted by virtue of torque angle between two terminal voltages. By varying this torque angle, the power over an a.c. line can be transmitted even if the two terminal voltages are equal in magnitude. Therefore it becomes clear that there is a fundamental difference in the principles of a.c. and d.c. power transmission.

5.2. POWER FLOW EQUATIONS:

On the basis of analysis given in chapter 2 simple d.c. system can be converted into an equivalent system which behaves similar to a two machine a.c. system .

System given in figure 5.1. can be reduced into an equivalent system as shown in figure 5.2(b) and 5.2(c). Power flow characteristics of a simple two machine a.c. system[12] are given by the following conventional equations.

$$P_1 = \frac{E_1^2}{Z} \sin\alpha_1 + \frac{E_1 E_2}{Z} \sin(\delta_{12} - \alpha_1)$$

$$P_2 = \frac{E_2^{\,2}}{Z} \sin \alpha_2 + \frac{E_1 E_2}{Z} \sin (\delta_{21} - \alpha_2)$$

P_1 and P_2 denote the power 'from' or 'to' machine '1' and '2' respectively, and $\alpha = (90 - \theta)$, $\theta = \tan^{-1}\frac{x}{r}$

$$\delta_{12} = -\delta_{21} = \text{torque angle}$$

To write the power angle characteristics of a d.c. system represented by figure 5.1(a), first this system is converted into equivalent a.c. system as shown in figure 5.1.(b) and (c) and then on the basis of above equations. The power angle equations are written as:-

$$P_1 = \frac{E_1^2}{\lambda^2 Z_s} \operatorname{Sin} \alpha_1 + \frac{E_1 E_2}{\lambda Z_s} \sin (\delta_{12} - \alpha_1) \quad ..5.2.$$

$$P_2 = \frac{E_2^2}{Z_r} \operatorname{Sin} \alpha_2 + \frac{E_1 E_2 \lambda}{Z_r} \operatorname{Sin} (\delta_{21} - \alpha_2) \quad ..5.3.$$

where

$\alpha_1 = (90 - \phi_s)$

$\alpha_2 = (90 - \phi_r)$

It can be seen from eqn. (5.2.) and (5.3.), that the power angle characteristics for such a d.c. system will differ from the characteristics of two machines a.c. system ~~ways~~ in two main ways.

1. In a.c. system, resistance can be neglected and thus the power angle characteristics assume a sinusoidal wave form. In d.c. system, because of non linear converter characteristics, an impedance is introduced and so the power angle characteristics will not be a sine curve.

2. In a.c. system power transmitted is equal to power received (i.e. $P_1 = P_2$) for a lossless line, but in d.c., P_1 is not equal to P_2 because of losses involved in converting devices.

5.3. PARALLEL A.C. AND D.C. SYSTEM:

We shall not deal with the system represented by figure 5.2. instead, we will consider a combined (parallel a.c. and d.c.) system as shown in figure 5.3. Equivalent circuit and vector relationship are shown in Figure 5.4 and 5.5 respectively. When both a.c. and d.c. systems operate in parallel, the total transmission capacity is divided between the two.[10,13,14] Following analysis will give the combined characteristics of such system.

Neglecting the resistance of the system

Let $Z = X_1 + X_2$

The power output of generator

$$P_1 + jQ_1 = \frac{E_1(E_1 - E_2 - X_2 Ia)}{Z}$$

$$= \frac{E_1^2 - E_1 E_2 - X_2 Ia\, E_1}{Z}$$

$$= \frac{1}{Z}\left[E_1^2 e^{j\frac{\pi}{2}} - E_1 E_2 e^{j(\frac{\pi}{2}+\delta_{12})} - X_2 I a E_1 e^{j(\delta_r - \phi_r)}\right] \quad (5.4)$$

and the power input to motor (2)

$$P_2 + jQ_2 = -\frac{1}{Z}(E_2 - E_1 - Ia.X_1)E_2$$

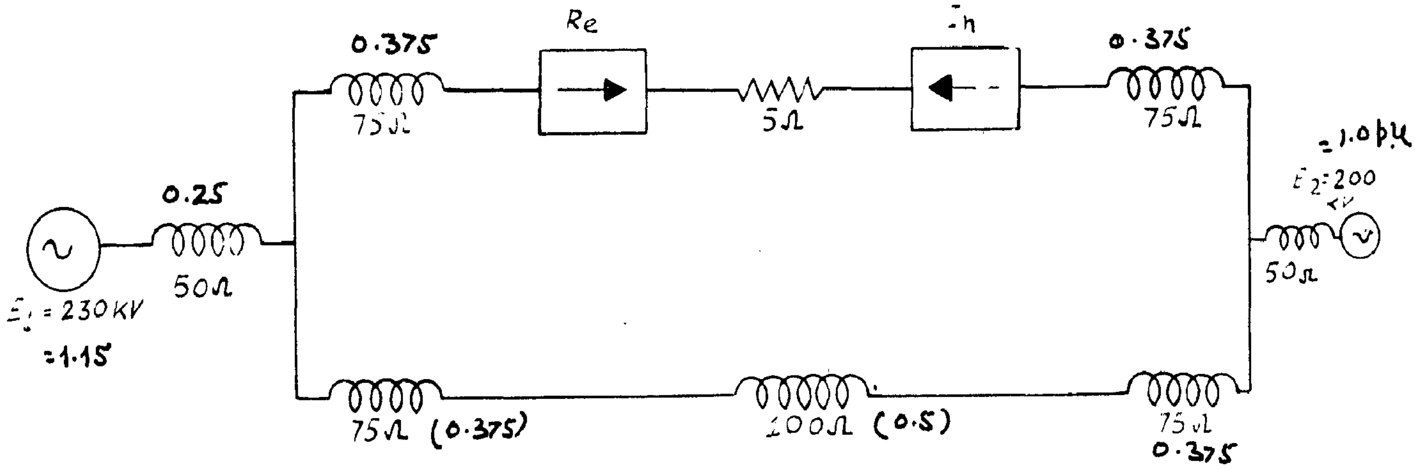


FIGURE 5.3 ASSUMED SYSTEM (GENERATOR TRANSFORMER AND LINE REACTANCES REPRESENTED)

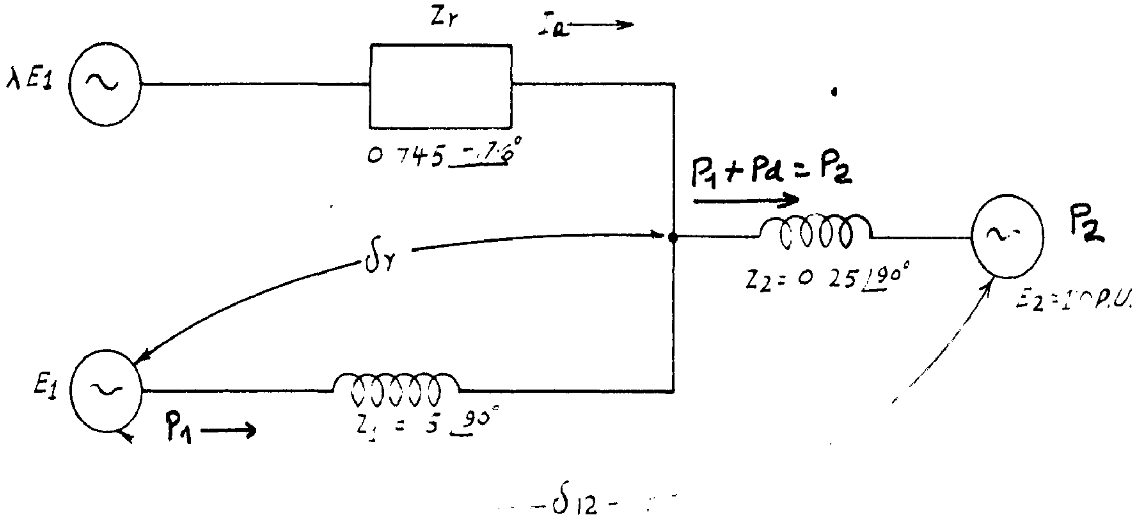


FIGURE 5.4 SIMPLIFIED PARALLEL A.C. AND D.C. SYSTEM FOR ANALYSIS.

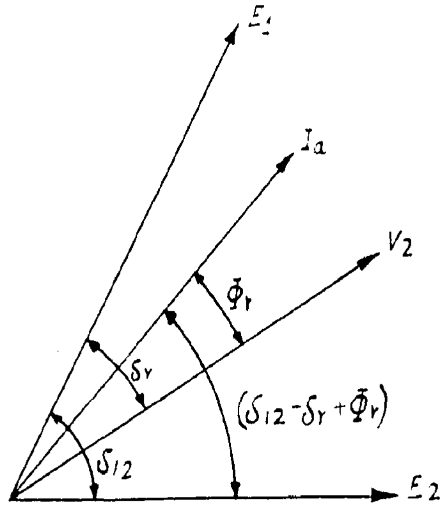


FIGURE 5.5 VECTOR DIAGRAM FOR FIGURE 5.4

$$= -\frac{1}{Z}\left(E_2^2 - E_1E_2 - Ia\ X_1\ E_2 \right)$$

$$= \frac{1}{Z}\left[E_2E_1\ e^{j(\frac{\pi}{2}-\delta_{12})} - E_2^2\ e^{j\frac{\pi}{2}} + Ia X_1 E_2\ e^{j(\delta_r - \delta_{12} - \phi_r)}\right] \quad (5.5)$$

As a matter of fact, above equations (5.4) and (5.5) are similar to the power flow equations for a two machine a.c. system except that in this case account has been taken of the fact that d.c. line also contributes to power flow and thus as it is obvious, P_1 and P_2 are affected by the presence of d.c. link.

Separating Real and imaginary parts of equation 5.4. and 5.5, we get, active components as

$$P_1 = \frac{1}{Z}\left[- \text{Cos}\ (90 + \delta_{12})\ E_1E_2 - \text{Cos}\ (\delta_r - \phi_r) Ia\ X_2E_1\right)$$

or $$P_1 = \frac{1}{Z}\left[E_1E_2\ \text{Sin}\,\delta_{12} - E_1\ Ia\ X_2\ \text{Cos}\ (\delta_r - \phi_r)\right] \quad ...(5.6)$$

$$P_2 = \frac{1}{Z}\left[E_1E_2\ \text{Cos}\ (90 - \delta_{12}) + Ia\ X_1\ E_2\ \text{Cos}\ (\delta_r - \delta_{12} - \phi_r)\right]$$

$$= \frac{1}{Z}\left[E_1E_2\ \text{Sin}\,\delta_{12} + X_1\ Ia\ E_2\ \text{Cos}(\delta_r - \delta_{12} - \phi_r)\right]$$

$$= \frac{1}{Z}\left[E_1E_2\ \text{Sin}\ \delta_{12} + Ia\ X_1\ E_2\ \text{Cos}\ (\delta_{12} - \delta_r + \phi_r)\right] \quad (5.7)$$

and Reactive Part,

$$Q_1 = \frac{1}{Z}\left[E_1^2\ \text{Sin}\ 90 - E_1E_2\ \text{Sin}\ (90 + \delta_{12}) - X_2I_aE_1\ \text{Sin}\ (\delta_r - \phi_r)\right]$$

$$Q_1 = \frac{1}{Z}\left[E_1^2 - E_1E_2 \text{Cos}\,\delta_{12} - X_2I_a\ E_1\ \text{Sin}(\delta_r - \phi_r)\right] \quad (5.8)$$

Similarly

$$Q_2 = \frac{1}{Z}\left[E_1E_2\ \text{Sin}(90 - \delta_{12}) - E_2^2\ \text{Sin}\ 90\right.$$

$$\left. + X_1I_a\ E_2\text{Sin}\ (\delta_r - \delta_{12} - \phi_r)\right]$$

$$= \frac{1}{Z}\Big[E_1E_2 \cos\delta_{12} - E_2^2 + X_1 I_a E_2 \sin(\delta_r - \delta_{12} - \phi_r)\Big] \qquad (5.9)$$

In the combined system when d.c. line does not take any load i.e. $I_d = 0$, therefore $I_a = 0$

($I_a = KId$ = equivalent a.c. current)

Substituting, $I_a = 0$, eqn. 5.6 and 5.7. become

$$P_1 = \frac{E_1E_2 \sin\delta_{12}}{Z} \qquad \text{from } ..5.6.$$

$$P_2 = \frac{E_1E_2}{Z} \sin\delta_{12} \qquad \text{from } ..5.7.$$

which are equations for two machine a.c. system.

To calculate P_1 and P_2 and to plot power angle characteristics (from eqn. 5.6 and 5.7.) it is essential to know the values of I_a and δ_r. These values can be found from the following equations derived in Chapter 2.

$$0 = -E_2Y_2 \cos(\delta_{12} + \phi_r - \delta_r) + E_1Y_1 \cos(\phi_r - \delta_r) + \lambda E_1 Y_r \sin\phi_r \qquad (5.10)$$

and

$$I_a = E_1Y_1 \sin(\phi_r - \delta_r) - E_2Y_2 \sin(\delta_{12} + \phi_r - \delta_r) - \lambda E_1 Y_r \cos\phi_r \qquad (5.11)$$

As an example, we will assume the system of figure 1.7 and calculate the power angle characteristics.

Neglecting resistance the system can be represented by pure reactances as shown in figure 5.3.

For convenience, we will calculate on per unit basis [15] assuming the following base quantities.

Base Voltage = 200 KV (Line to Line)

Base Power = 200 MVA(3 Phase)

$$\text{Base Current} = \frac{200 \times 10^6}{\sqrt{3} \times 200 \times 1000} = 578 \text{ Amps.}$$

$$\text{Base Impedence} = \frac{(KV_{base})^2}{(MVA_{base})} = \frac{40000}{200}$$

$$= 200 \text{ Ohm.}$$

Let

Generator Voltage, $= E_1 = 230$ KV(Line to Line)

Load Voltage $= E_2 = 200$ KV(Line to Line)

Angle of delay of rectifier $\alpha = 10^0$

Angle of overlap of rectifier $\gamma_s = 5^0$

Angle of deionisation of Inverter $\delta_r = 15^0$

Angle of overlap of inverter $\gamma_r = 5^0$

Therefore, $(\alpha + \gamma_s) = 15^0$

$\beta = (\delta_r + \gamma_r) = 20^0$

$\cos \phi_r = \frac{1}{2} (\cos \beta + \cos \delta_r)$ from eqn. 2.22

$= 0.953$

$\phi_r = 17.6^0$

$\sin \phi_r = 0.3$

$R' =$ Total resistance of d.c. line $= \frac{3}{\pi}(X_s + X_r) + R$

$= 148.5$ Ohms.

Assuming rectifier and inverter have similar connections so that

$$K_1 = K_2 = \frac{3\sqrt{2}}{\pi}$$

$$K_3 = K_4 = \frac{\sqrt{6}}{\pi}$$

Equivalent impedance of d.c. line

$$Z_r = \frac{R^1 \angle -\phi r}{K_1 K_4 \cos\beta} \qquad \text{from eqn. 2.10}$$

$$= \frac{148.5 \angle -\phi r}{\frac{3\sqrt{2}}{\pi} \; \frac{\sqrt{6}}{\pi} \; X 0.94 \; X 200} \text{ p.u.} = 0.745 \angle -\phi_r \text{ p.u.}$$

$$E_1 = \frac{230}{200} = 1.15 \text{ p.u.}$$

$$E_2 = \frac{200}{200} = 1.0 \text{ p.u.}$$

$$\lambda = \frac{K_1 \cos\alpha}{K_2 \cos\beta}$$

$$= \frac{0.966}{0.94} = 1.027$$

$$\lambda E_1 = 1.15 \; X \; 1.027$$

$$= 1.182 \text{ p.u.}$$

On the basis of theory given in Chapter 2, the system of figure 5.3. can be reduced as system of figure 5.4. in which

$$Z_1 = 300 \text{ Ohms} \quad 1.5 \text{ p.u.}$$

$$Z_2 = 50 \text{ Ohms.} = .25 \text{ p.u.}$$

$$\therefore \quad Y_1 = \frac{1}{1.5} = 0.666 \text{ p.u.}$$

$Y_2 = \frac{1}{0.25} = 4.0$ p.u.

$Y_r = \frac{1}{0.745} = 1.34$ p.u.

To calculate the power flow from equations(5.6) and (5.7) we have three unknowns δ_{12}, δ_r & I_a .The values of I_a and δ_{12} are calculated from equations 5.10 and 5.11. First of all any arbitrary value of δ_r is substituted in equation 5.10 otherthings being known, δ_{12} is found from 5.10 and substituted in eqn. 5.11 from 5.11; I_a is then calculated. For these values, corresponding values of P_1 and P_2 are calculated.

Substituting the above calculated values in equation 5.10 and 5.11, we get

$$0 = -E_2 Y_2 \cos(\delta_{12} + \phi_r - \delta_r) + E_1 Y_1 \cos(\phi_r - \delta_r) + \lambda E_1 Y_r \sin \phi_r$$

which reduces to

$$4 \cos(\delta_{12} + \phi_r - \delta_r) = 1.15 \times .666 \cos(\phi_r - \delta_r) + 1.18 \times 1.34 \times .3$$

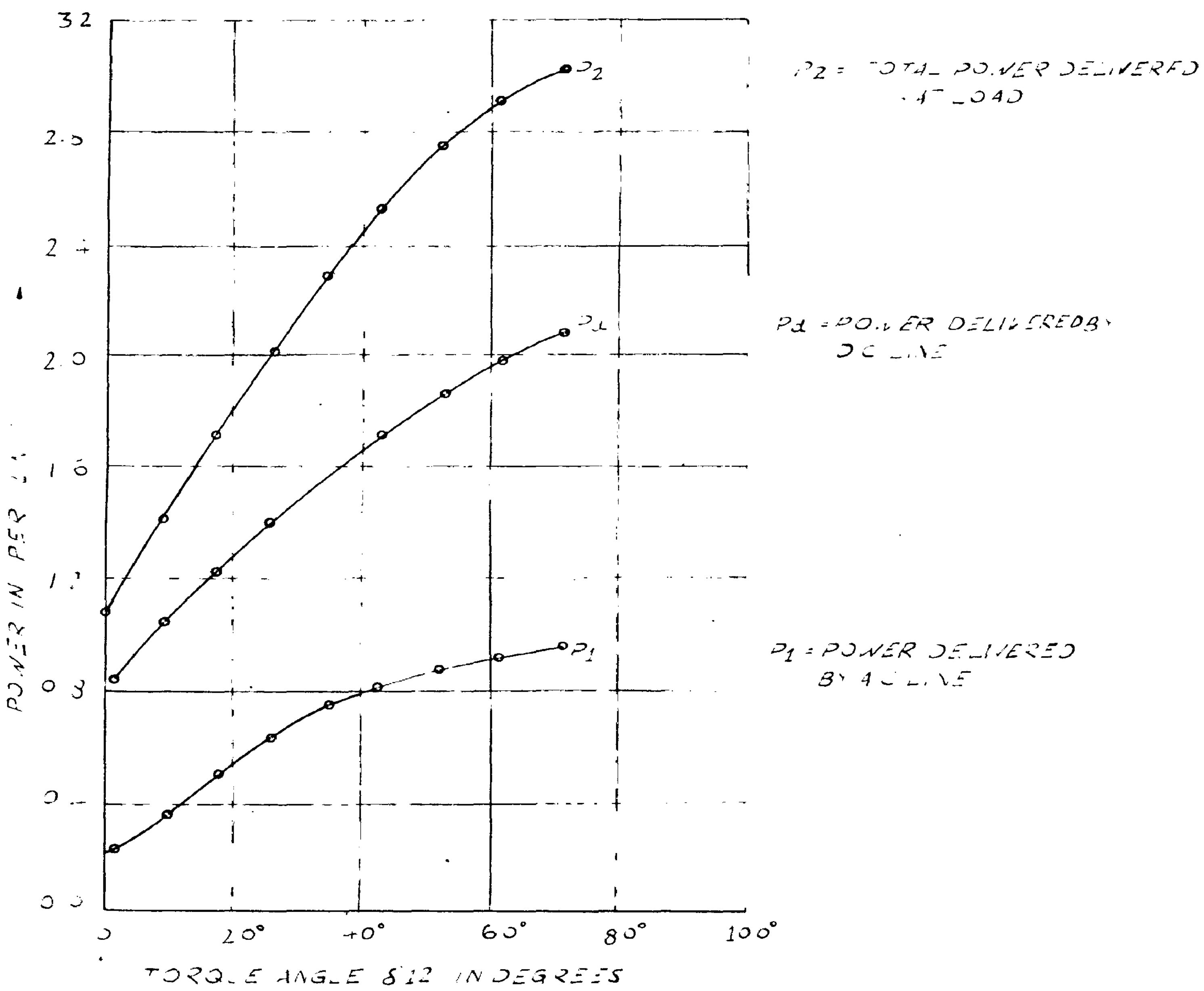
Let $(\phi_r - \delta_r) = \theta_k$

$$\cos(\delta_{12} + \theta_k) = 0.191 \cos \theta_k + 0.119 \qquad .....(a)$$

giving different values to δ_r (hence θ_k), we calculate corresponding values of δ_{12}. Substituting these values of θ_k and δ_{12} in eqn. 5.11, we know the value of EId. from the following equations:

$$EId = I_a = 0.765 \sin \theta_k - 4 \sin(\delta_{12} + \theta_k) - 1.51 \qquad ....(b)$$

These values of I_a and θ_k are substituted in equations (5.6) and (5.7) and power angle equations then can be simplified as:-



3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
POWER IN PER
0
20°
40°
60°
80°
100°
TORQUE ANGLE δ12 IN DEGREES
P2
P1
P2 = TOTAL POWER DELIVERED AT LOAD
P1 = POWER DELIVERED BY DC LINE
P1 = POWER DELIVERED BY AC LINE

GRAPH 5.1

$$P_1 = 0.6.6 \sin \delta_{12} - 0.2875\, I_a \cos \phi' \quad \ldots$$

$$P_2 = 0.606 \sin \delta_{12} + 1.5\, I_a \cos (\delta_{12} + \theta_k)$$

Power delivered by d.c. line is equal to $(P_2 - P_1)$.

Table 1 shows the calculated results which have been lotted on graph 5.1.

5.4. POWER TRANSMITTED OVER D.C. LINE:[13]

Power transmitted over a d.c. line is given by

$$P_d = (K_1 E_1 \cos\alpha - R_1 I_d)\, I_d. \qquad \ldots.(5.12)$$

Where

R_1 = Equivalent resistance of rectifier

Z = Total resistance of d.c. circuit.

$$I_d = \frac{(K_1 E_1 \cos\alpha - K_2 E_2 \cos\beta)}{Z} \qquad \ldots.(5.13)$$

Substituting for I_d in equation 5.12

$$P_d = K_1 E_1 \cos\alpha\, I_d - \frac{(K_1 E_1 \cos\alpha - K_2 E_2 \cos\beta)^2 R_1}{Z^2}$$

Simplifying we get

$$P_d = \frac{1}{Z^2}\left[(Z-R_1)(K_1E_1\cos\alpha)^2 + (2R_1 - Z)\, K_2E_2\cos\beta \cdot K_1E_1\cos\alpha - R_1(K_2E_2\cos\beta)^2\right] \quad \ldots 5.14$$

Equation 5.14 shows that the d.c. power can be varied by exercising the control of switching angles of rectifier and invertor. The power variation is possible even if the terminal voltages are kept constant. In case of a.c., no such method is adoptable to control the power except by voltage variation.

Equation 5.12 can also be expressed as

$$P_d = \frac{(E_1 K_1 \cos\alpha - E_2 K_2 \cos\beta)}{Z} E_1 K_1 \cos\alpha \quad .. (5.14)(a)$$

Equation 5.14 shows that variation of d.c. power is affected by the system parameters E_1, E_2, α, or β,

By means of an example, we will study the effect of variation of d.c. power when sending end voltage drops and inverter firing angle changes.

Taking parameters of example of Section 5.3.

Let $\alpha = 20^0$

$\beta = 30^0$

$E_2 = 200$ KV

$K_1 = K_2 = \frac{3\sqrt{2}}{\pi}$

$K_1 \cos\alpha = \frac{3\sqrt{2}}{\pi} \cos 20^0 = 1.27$

$(K_1 \cos\alpha)^2 = 1.62$

$E_{d2} = \frac{3\sqrt{2}}{\pi} (\cos 30) \times 200$

$= 239$ KV

$E_{d2}^2 = 5,7000$

$Z = 140$ Ohms.

$R_1 = 71.5$ Ohms.

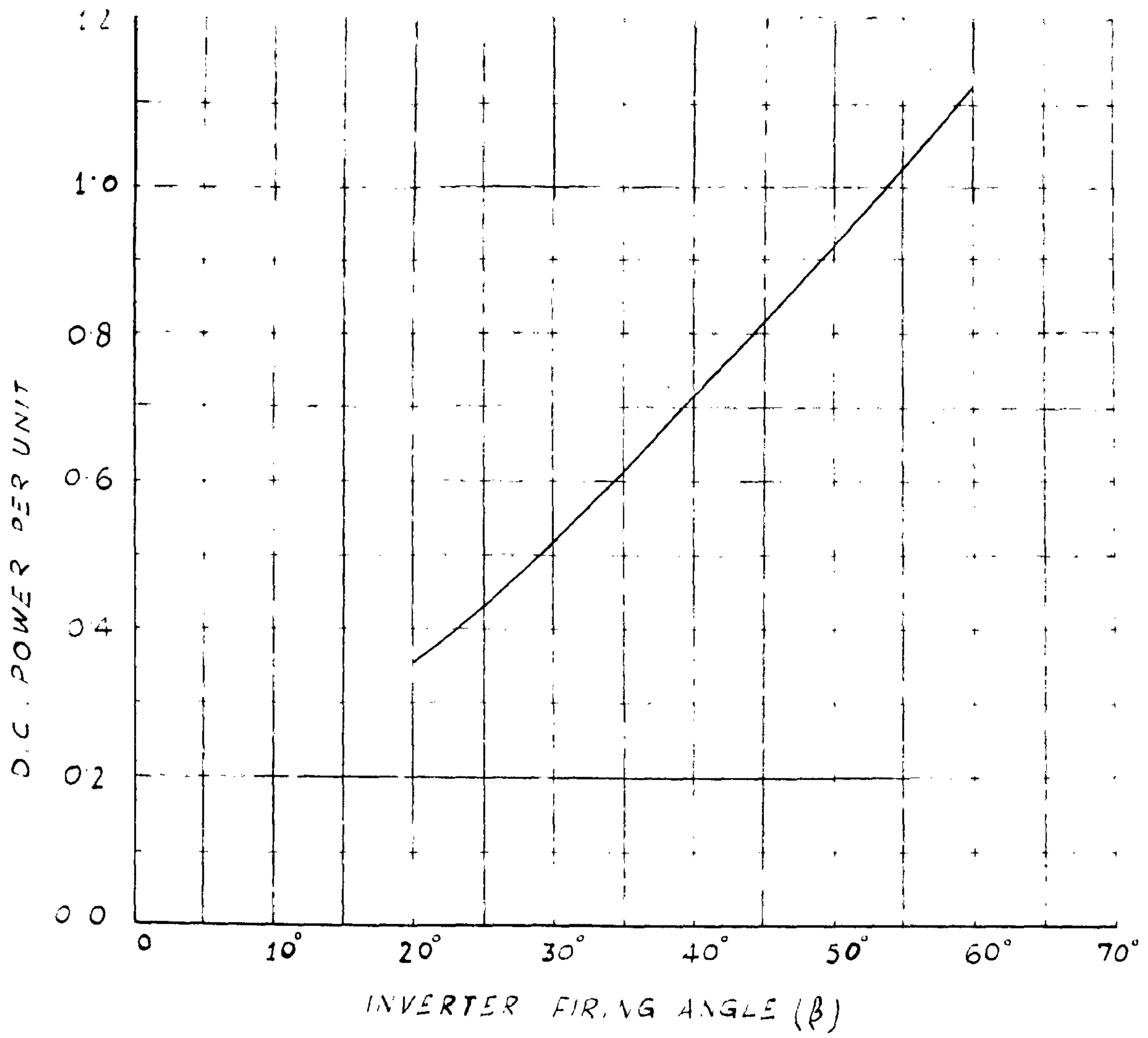
$(Z - R_1) = 76.5$ Ohms.

$(2 R_1 - Z) = -5$

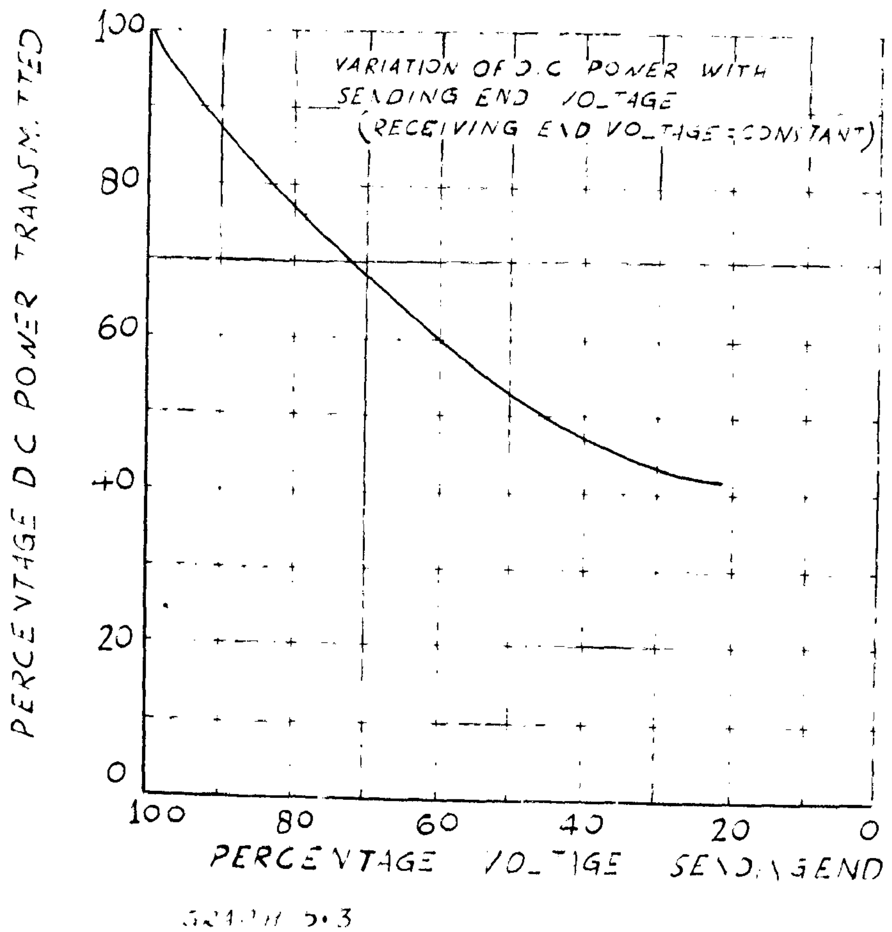
Substituting in eqn. 5.14 we get

$$P_d = \frac{1}{2.2} (.0124 E_1^2 - .1935 E_1 + 470) \text{MW}. \quad ....$$

(Where E_1 is in KV)



GRAPH 5.2 VARIATION OF D.C. POWER WITH INVERTER FIRING ANGLE



GRAPH 5.3

Calculated results are tabulated in Table 2 . Graph 5.3. shows the variation of d.c. power when sending end voltage falls. As it is expected transmitted power also reduces considerably. Another graph 5.2. shows variation of d.c. power with inverter's firing angle. The power increases with firing angle(Table 2 b).

5.5. LIMITING RATIO OF A.C. AND D.C. POWER FOR A GIVEN STATIC CONDENSER CAPACITY:

One of the several methods to meet the reactive power demand, is to install the static capacitors on the a.c. side of the inverter. These are rated to deliver the required amount of KVAr. If a static capacitor is rated for a particular value of current, it will fail when current exceeds its rated value. Therefore the system will become unstable on account of interruption of required KVAr. supply. We will take here a simple case to find the limiting ratio of d.c. to a.c. power for stability of inverter. Considering the following system with given assumptions:-

1. Generator Voltage E_1 remains constant.
2. Load voltage E_2 varies to take into account the load fluctuations in the system.
3. Alternating current corresponding to a particular setting, remains constant. This current setting can be changed by regulating equipment.
4. Load is situated at the inverter transformer secondary, as such, to neglect the line impedance.
5. Resistance of the system is neglected.

Following relations will be used:-

$$I = \frac{\sqrt{6}}{\pi} I_d \qquad \ldots.(5.15)$$

$$I_d = \frac{E^2}{\sqrt{2}\,\omega L_2}\,(\cos\delta - \cos\beta) \qquad \ldots 5.16$$

Active power from inverter $P = \sqrt{3}\,E_2 I_L \cos\phi$ ...5.17

Power factor at the a.c. side of inverter

$\cos\phi = \frac{1}{2}(\cos\delta + \cos\beta)$ ...5.18

Q = Reactive power needed = $\sqrt{3}\,E_2 I \sin\phi$ ...5.19

Substituting value of I_d from 5.1 in 5.16 we get

$$(\cos\delta - \cos\beta) = \frac{\sqrt{2}\,.X}{E_2}\cdot\frac{\pi}{\sqrt{6}}\,I \qquad \ldots 5.20$$

Let

$\delta = 10^\circ$

$\cos\delta = 0.9848$

Here variation of power (active and reactive) will be calculated for constant value of alternative current and varying receiving end voltage.

i) for $I = 500$ Amps.

$$\cos\beta = \cos\delta - \frac{75 \times \pi \times 500}{\sqrt{3}\,E_2 \times 1000}$$

$$\cos\beta = 0.9848 - \frac{68}{E_2} \qquad E_2 \text{ in KV(L-L)}$$

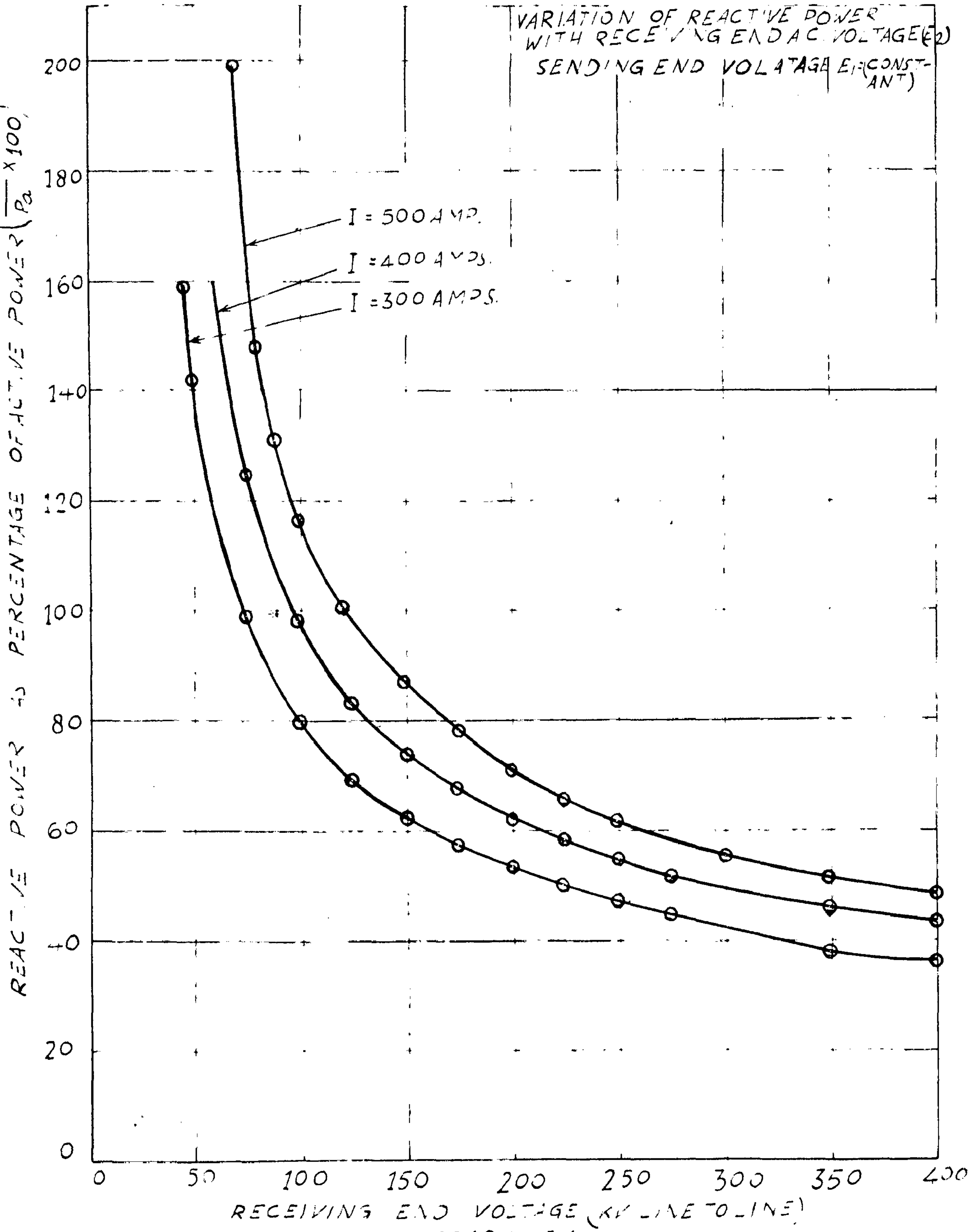
ii) for $I = 400$ Amps

$$\cos\beta = \cos\delta - \frac{75 \times \pi \times 400}{\sqrt{3} \times E_2 \times 1000}$$

$$= .9848 - \frac{54.4}{E_2}$$

iii) Similarly for $I = 300$ Amps.

$$\cos\beta = .9848 - \frac{40.7}{E_2}$$



VARIATION OF REACTIVE POWER WITH RECEIVING END AC VOLTAGE (E2)
SENDING END VOLATAGE E1 (CONSTANT)
I = 500 AMP.
I = 400 AMPS.
I = 300 AMPS.
REACTIVE POWER AS PERCENTAGE OF ACTIVE POWER ($\frac{Pr}{Pa}$ x 100)
200
180
160
140
120
100
80
60
40
20
0
0
50
100
150
200
250
300
350
400
RECEIVING END VOLTAGE (KV LINE TO LINE)

GRAPH 5.4

Calculated values have been tabulated in Table 5. The results have been plotted in graph 5.4.

Let static capacitor be rated to deliver 100 MVA at 500 Amperes.

P = Active power delivered by D.C. Link

Q = reactive power required for inverter.

Load voltage = E_2 = 200 KV, X = 300 Ohms.

From graph 5.4. at 200 KV, $\frac{Q}{P}$ = tan ϕ = .53

$\phi = 27.8^{o}$

Sin ϕ = .466

$MVA = \frac{100}{.466} = E_2 I = E_2 . E_2 \omega C.$

$$C = \frac{100.10^{-6}}{5.85 \times 3}$$

~~5.85 X 3~~

$$C = \frac{17.1}{3} = 5.7 \mu F.$$

A.C. Power is given by $= \frac{E_1 E_2}{X} \sin \delta_{12}$

Maxm. a.c. power at $\delta_{12} = 90^{o}$

$$= \frac{230 \times 200 \times 10^{6}}{3 \times 300}$$

P_{ac} = 51.1 MW

Q = Reactive Power = 100 MVAr.

and $\frac{Q}{P} = 0.53$

$P = \frac{100}{0.53}$ = 189 MW.

Limiting ratio of d.c. to a.c. power $= \frac{189}{51.9}$

= 3.64.

5.6. SUMMARY:

Analysis of parallel a.c. and d.c. system is difficult and time consuming. It involves the evaluation of several unknowns for each value of torque angle in accordance with equation 5.6 and 5.7. A set of power angle characteristics is plotted assuming arbitrary parameters.

It is seen from graph 5.1. that power delivered by a.c. line is only a small portion of total load. Major portion of a load power is delivered by d.c. line . It is observed that steady state stability limit is reached at about 73° torque angle which is less than the limiting value of torque angle in case of a pure a.c. system. So far as the power level is concerned, it is highly increased. If we compare the power of parallel a.c. and d.c. system with a similar system in which d.c. line is replaced by a.c. line, we find maximum power if d.c. is replaced by a.c.

$$= \frac{E_1 E_2}{X_{eq.}} \sin \delta_{12}$$

where

$X_{eq.}$ is the combined reactance of both the lines

$$X_{eq.} = 0.25 + \frac{1.25}{2} + 0.25$$

$$= 1.125$$

$$\text{Maximum power} = \frac{1.15}{1.125} \sin 90^{\circ}$$

$$= 1.022 \text{ p.u.}$$

Comparing the power in both cases, it is seen that when a.c. line is paralleled by a d.c. line in the system, power transmitting capacity of the system is increased.

Graph 5.2. shows the variation of d.c. power with inverter firing angle. It is seen that d.c. power increases sharply with firing angle. However, it can be noted that this will be followed by an increased demand of reactive power. Thus if sufficient means to supply reactive power are available, firing angle can be increased to raise d.c. power. Graph 5.3. shows the effect of falling the sending end voltage. The transmitted power also drops down as is indicated in the graph. For a given capacity to supply reactive power, there is a limiting ratio of d.c. to a.c. power, which can be transmitted without failure of inverter on account of interruption in reactive power supply. This ratio has been calculated in section 5.5.

TABLE 1

$\theta_{II} = (\phi_r - \delta_r)$	0	10°	20°	30°	40°	50°	60°	70°	60°
$\cos(\delta_{12}+\theta_{II})$	•31	•307	•2985	•2845	•265	•242	•2145	•1844	•1522
$(\delta_{12}+\theta_{II})$	72°	72.1°	72.7°	73.5°	74.6°	76°	77.6°	79.4°	81.2°
I_a p.u.	5.31	5.18	5.068	4.957	4.869	4.814	4.748	4.722	4.7
δ_{12} degrees	72°	62.1°	52.7°	43.5°	34.6°	26°	17.6°	9.4°	1.2°
P_1 p.u.	•952	•930	•833	•816	•725	•623	•499	•365	•2225
P_2 p.u.	3.046	2.915	2.752	2.527	2.280	2.016	1.713	1.409	1.087
P_d p.u.	2.094	1.935	1.869	1.711	1.455	1.393	1.2145	1.044	0.865

[illegible] - 2 [illegible] 5.3.

V[illegible] [illegible]

[illegible]	100	95.7.	91.2	87	76	65.2	54.4	43.5	32.6	21.7	17.4	10.0
F_d	100	94.5	89.8	84.7	73.7	64.4	56.5	49.3	45.4	41.9.	41.1	13.8

Using equation 5.14, taking $E_1 = 230$ kV, $E_2 = 200$ kV and other values as on page 47, the expression for D.C. Power reduces to

$$P_{d.c.} = 296 - 18.3\cos\beta - 233\cos^2\beta$$

; from which we calculate as below:-

TABLE 2 (b)

VARIATION OF D.C. POWER WITH INVERTER FIRING ANGLE (β)

(Graph 5.2)

β (degrees)	20	25	30	40	50	60
P_{dc} (per unit)	0.355	0.435	0.526	0.725	0.932	1.14

TABLE - 9

GRAPH 5.4

a) I = 300 Amp.

E(KV)	45	50	75	100	125	150	175	200	225	250	275
$\frac{C}{P}$ ( )	159	142	93.5	79.6	69.5	62.5	57	53.3	51	47.2	44.8

b) I = 400 Amp.

E(KV)	60	75	100	125	150	175	200	225	250	275
$\frac{C}{P}$( )	159	125	98.5	83.7	74	68	62	50	54	52

c) I = 500 Amp.

E(KV)	70	80	90	100	120	130	140	150	175	200	225	250	275
$\frac{C}{P}$( )	199	148	131	117	101	96	91	88	78	71	66	62.5	59

CHAPTER - 6

CHAPTER – 6

6.1. [illegible] (12,15,16)

Study of system stability is important from the point of view that it gives an idea of the system behaviour under abnormal operating conditions. Associated conventional terms both steady state and transient stability have to be given due consideration before deciding the suitability of a particular system. A brief discussion will be made here regarding the stability of parallel a.c. and d.c. system.

6.2. [illegible] (11,12,13,14,15)

The effect of operating d.c. transmission line in parallel with a.c. system can be seen from graph 5.1. where the power angle characteristics of the combined system have been plotted.

If we replace the d.c. line by a line similar to that of paralleled a.c. line and system is made to operate as a double circuit a.c. system, the new power angle characteristics of this system will be sinusoidal in nature (neglecting resistance) and the maximum steady state power which can be transmitted corresponding to torque angle of 90°, is given by the well known relation

$$P_{max.} = \frac{V_1 V_2}{X} \sin 90^{\circ}$$ substituting the values assumed for parallel system.

$$= \frac{1.15}{1.12} = 1.022 \text{ p.u.}$$

It is observed from combined characteristics of graph 5.1. that the maximum steady state power transmitted by combined system is 3.046 per unit which is high enough in comparison to the maximum power transmitted by a double circuit a.c. system. This considerable increase in steady state power limit goes in favour of using a d.c. link in parallel with a.c. line. This increase in power may be due to the fact that unlike a.c. system, the torque angle does not affect d.c. power. It is known that d.c. power depends on the voltage difference between the sending and receiving end, and can be increased by the increasing of the inverter advance firing angle. Graph 5.3. of Chapter 5 shows the effect of variation of inverter firing angle on the d.c. power. The stability under steady state can thus be increased by exercising the inverter control. The limitation comes only due to reactive power requirements. Experience in most of the d.c. projects has shown that inverters can be operated upto a firing angle of 60°. Hence quite a good amount of d.c. power can be achieved.

However, as indicated in graph 5.1. the angle at which the steady state power limit for a parallel a.c..d.c. system occurs is reduced and is about 73° in this case whereas it was 90° in the case of a simple a.c. system. This decrease is not objectionable from stability point of view because quite a good amount of power can be transmitted by having an effective control of inverter firing. It will not be superfluous to say that in d.c. system inverter advance firing angle serves the same purpose as torque angle in a.c. systems.

When d.c. power is increased, terminal voltage at inverter end tends to fall and there comes the need to supply more reactive power. Therefore it can be noted here that in order to improve steady state stability of a parallel a.c. d.c. system, an adequate amount of reactive power supply is necessary. Synchronous condenser or static capacitors if exist, their capacity increased. This is equivalent to reduction of series inductance in case of a.c. systems.

6.3. TRANSIENT STABILITY:[12,13,14,15]

Unlike in a.c., no simple method such as equal area criterion, to find transient power limit, is applicable for d.c. transmission. It is therefore difficult to predict the amount of power that can successfully be transmitted by a d.c. link. Further, the power carrying capacity of a d.c. link is limited only by the thermal rating of terminal equipments.

It has not yet been possible to give analytical expression to analyse the transient stability limit of a parallel a.c. and d.c. system. If we simplify the approach and assume that in a parallel system both a.c. and d.c. link will operate independent of each other, following explanation can however be given. In a combined system both a.c. and d.c. links are sharing load. Power angle characteristics of a.c. link will be sinusoidal and from equal area criterion, it can be found out that what is the transient power limit(P_m) for a.c. line for initial power level P_1 . (where P_1 is a power delivered by a.c. line in a combined system) It may be noted that lower the value of P_1, greater is the transient stability because torque angle delta,(δ),has got then more wide range of swing.

In a.c. system the restriction on transient stability is imposed because higher is the initial power, angle δ has lesser range of swing and more chances for machines to go out of step. Therefore in order to maintain stable operation under transient conditions, it is desirable that initially a.c. power level is kept low and d.c. is given a larger portion of load to share.

share. Under such conditions when initial power level is low if there comes a sudden load increase, the torque angle of a.c. system can have a wide range of variation to meet this increased load, thereby reducing the chance to loose stability. From graph 5.1. of Chapter 5, the characteristics of parallel a.c. and d.c. system, show that a.c. is taking only a small portion of load and most of the load is met by the d.c. line and this makes the system more stable.

6.4. BEHAVIOUR OF SYSTEM UNDER FAULT CONDITIONS. (1,10)

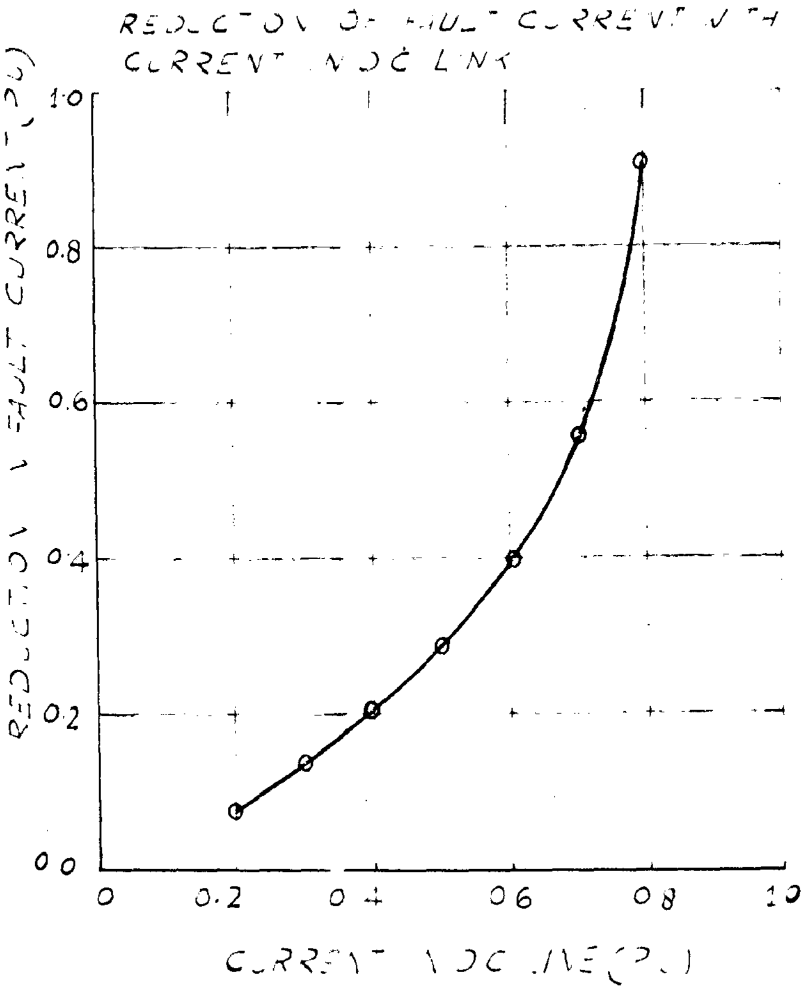
A system behaviour under fault conditions can be studied by considering a three-phase fault on the a.c. line, at receiving end. The voltage at the fault point reduces and transmitted power drops. A.C. power will be reduced considerably and the system may tend towards instability. Because of the reduced voltage at inverter end d.c. power will also be reduced. Moreover, the d.c. power can be maintained to a higher level by controlling the switching angle of inverter. Variation of power with inverter switching angle is shown in Figure 5.2.

6.5. EFFECT OF PRESENCE OF [illegible] VOLTAGE [illegible] A.C. FAULT CURRENT

We shall now consider the effect of presence of d.c. link on a.c. fault current when a fault occurs on the a.c. side of inverter as shown in figure 6.2. (5,8) The fault is fed by the current from d.c. line, generator and static capacitor. The right hand portion to the fault does not effect the analysis and hence it can be neglected.

Writing equation for current at node I.

$$I_2 \angle \phi - jI_0 \, [illegible] + \frac{E_1 - [illegible]}{[illegible]} = \frac{E}{Z_2} \qquad \ldots \quad 6.1$$



GRAPH 6.1

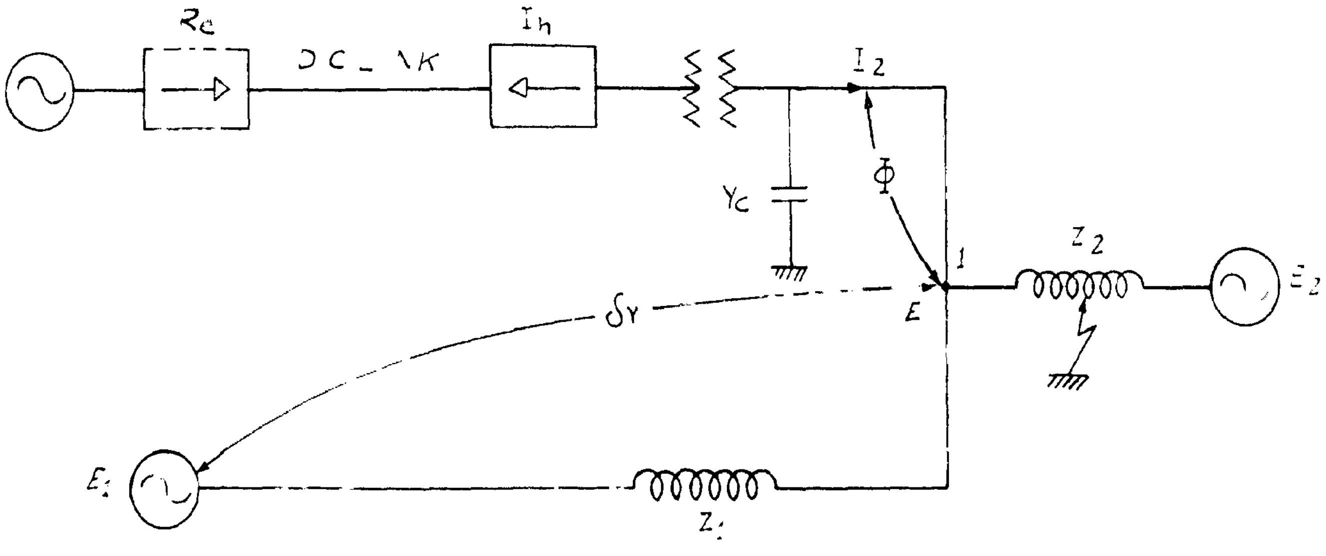


FIGURE 6.2

neglecting resistance,

$$Z_1 = X_1 \ \& \ Z_2 = X_2$$

$$I_2 \angle \phi - j Y_0 E + \frac{E_1 - E}{jX_1} = \frac{E}{jX_2} \qquad (6.2.)$$

equating real and imaginary parts on both the sides:-

$$j I_2 \sin \phi - j Y_0 E + \frac{E_1 \cos \delta r - E}{jX_1} = \frac{E}{jX_2}$$

$$-X_2 I_2 \sin \phi + X_2 Y_0 E + E_1 \frac{X_2}{X_1} \cos \delta r - \frac{E X_2}{X_1} = E$$

$$-X_2 I_2 \sin \phi + E_1 \frac{X_2}{X_1} \cos \delta r = E\left(1 + \frac{X_2}{X_1} - Y_0 X_2\right)$$

$$\frac{-X_1 X_2 I_2 \sin \phi + E_1 X_2 \cos \delta r}{X_1} = \frac{E \,(X_1 + X_2 - Y_0 X_2 X_1)}{X_1}$$

$$E = \frac{X_2 E_1 \cos \delta r - X_1 X_2 I_2 \sin \phi}{X_1 + X_2 - X_1 X_2 Y_0} \qquad (6.3)$$

Equating real parts of equation 6.2.

$$I_2 \cos \phi + \frac{E_1}{X_1} \sin \delta r = 0$$

$$\sin \delta_r = - \frac{X_1 I_2}{E_1} \cos \phi \qquad (6.4.)$$

To calculate fault current, we divide eqn. 6.3. by X_2,

(since fault current $= \frac{E}{X_2}$)

fault current

$$I_f = \frac{E_1 \cos \delta r - X_1 I_2 \sin \phi}{X_1 + X_2 - Y_0 X_1 X_2} \qquad (6.5).$$

Equation 6.5. gives the fault current with d.c. link present

Fault current without d.c. link(i.e. when $I_2 = 0$) = I_{f1}

$$I_{f1} = \frac{E_1}{X_1 + X_2 - Y_0 X_1 X_2} \qquad \text{...6.6.}$$

Comparing equation 6.5 and 6.6,

$(I_{f1} - I_f)$ = {fault current without d.c. - fault current with d.c. } .

$$= \frac{E_1 - E_1 \cos \delta r + X_1 I_2 \sin \phi}{X_1 + X_2 - Y_c X_1 X_2}$$

$$= \frac{E_1(1 - \cos \delta r) + X_1 I_2 \sin \phi}{X_1 + X_2 - Y_c X_1 X_2} \qquad (6.7)$$

Now if $(I_{f1} - I_f) > 0$

This indicates that fault current is reduced with the presence of d.c. link.

Example: Let us assume the following system as shown in Figure 6.2 with the parameters as given:

Assuming Z_1 & Z_2 are purely inductive

E_1 = 1.15 p.u.

X_1 = 1.5 p.u.

X_2 = 0.25 p.u.

Sin ϕ = 0.3

Cos ϕ = 0.953

C = 5.7 μF

Frequency = 50 C/S

∴ Y_c = 0.398 p.u.

$2\pi f = 314$

$$\omega C = 314 \times 5.7 \times 10^{-6}$$

$$\frac{1}{\omega C} = \frac{1}{314 \times 5.7 \times 200 \times 10^{-6}}$$

$\omega C = 0.358$

$Y_c = 0.358$ p.u.

From equation 6.4, $\sin \delta_r = \frac{-X_1 I_2}{E_1} \cdot \cos \phi$

$$= 1.245\, I_2$$

Using equation 6.7 to calculate

$$(I_{g1} - I_g) = \frac{E_1(1 - \cos \delta_r) + X_1 I_2 \sin \phi}{X_1 + X_2 - Y_c X_1 X_2}$$

Substituting values,

$$(I_{g1} - I_g) = \frac{1.15(1 - \cos \delta_r) + 1.5 \times 0.3 \times I_2}{(1.75 - .134)}$$

$$= \frac{1.15\,(1 - \cos \delta_r) + .5\, I_2}{1.616}$$

Calculations have been made for the assumed system of figure 6.2. Results are tabulated in table 1 and plotted on graph 6.1. It is seen that as current in d.c. link increases, more reduction in fault current is observed. This is in favour of making interconnections by d.c. link.

6.6. [illegible]

Working principle and fundamental relations of inverter operation can be formed in references.(12,28) However, it will not be out of place to give here some salient features due to which instability of inverter comes to the picture.

The operation of rectifiers at an angle greater than 90° gives rise to inversion process. The power in this case is fed from d.c. line to a.c. system provided that the proper excitation at a.c. end is available.[128] Thus, for operation of a convertor as inverter, a.c. supply is essential. During process of inversion, inverters need reactive power for successful operation. Reactive power requirements for inversion have been discussed in Chapter 3. Besides reactive power requirements, firing angle of inverter also influences stability of inverter.[9,16] Dependence of voltage, current and power flow on firing angle has been brought out in Chapter 4.

From stability point of view, it can be mentioned here that during normal operation inverters are operated with as small firing angle as possible to keep the reactive power demands to a minimum. The operating experience in d.c. project has shown that a switching angle upto 60° can be comfortably accommodated in practice. A switching angle beyond 60° gives rise to excessively high reactive power requirements and there is possibility of inversion instability.

There is also limitation of minimum value of firing angle.[2] When firing angle falls below the minimum value of about 10°, grid loses control and so inverter fails to operate. For successful operation of inverter, this minimum value of firing angle should be large enough to allow time for proper deionisation of the valve before the next cycle of operation starts. Generally the deionisation angle is about 7° to 10° depending on particular type of valve. For stable inverter operation, it is essential that this minimum value of angle is always ensured so that grid control is effectively exercised.

Two types of control, namely constant current and constant firing angle control are used to control the d.c. power flow in the line. In the system where constant firing angle control is used, there are more chances to get instability, because in such types of systems for a load flow at constant voltage, firing angle is fixed. If due to increase of load current there is fall in voltage, both the changes will tend to increase the overlap angle. As a result deionisation angle δ will decrease according to following law:-

$$\beta = \delta + \gamma$$

under normal conditions, the fluctuations in γ are small and possibility of instability can be ignored. It has been shown[16] that due to reversal of invertor this angle is changed and stability problems may arise therefore.

[illegible] [16] - The simplest and efficient way to prevent failure of invertors is to provide a larger value of firing angle β such that deionisation angle δ never falls below the value required for the valve to get deionised before the next cycle of operation starts. Of course, this method gives a larger consumption of reactive power but the failure of valve is prevented. Greater is the firing angle, more is the possibility of a valve to remain stable under transient load fluctuations. In other words the safety of invertor operation is improved at the cost of reactive power.

6.7. CONCLUSION

On the basis of discussions carried out in this chapter, we can conclude that :-

1. Steady state power limit of a parallel a.c. and d.c. system is much more higher than the system without

d.c. link or with d.c. link replaced by a.c. link of the same capacity.

2. The torque angle at which the maximum power in a combined system occurs is less than 90°.

3. Transient stability can be improved if d.c. line shares a major portion of load.

4. More is initial d.c. power, more transient stability is improved. In other words, d.c. power acts as 'damping device' under transient conditions. Therefore it will be helpful towards stability if d.c. line is made to share a larger portion of load.

5. Larger capacity of reactive power available, will mean a more stable system.

6. Under fault conditions, as has been seen in section 6.5, if d.c. link is present, the fault current is reduced. This reduction of fault current becomes larger and larger as power delivered by d.c. line increases.

—

TABLE - 1

REDUCTION OF FAULT CURRENT WITH CURRENT IN D.C. LINE

I_2 p.u.	.2	.3	.4	.5	.6	.7	.8	.9
Sin δr	.249	.374	.499	.623	.747	.873	.995	
$1.15(1-\cos\delta_r)$	.1265	.219	.333	.475	.657	.897	1.47	
$(I_{f1}-I_f)$ pu.	.0784	.135	.206	.294	.406	.556	.91	

ADVANTAGES OF COMBINED A.C. AND D.C. SYSTEMS:

Some of the main advantages of combined a.c. and d.c. system on the basis of work done, are listed here:

1. Parallel a.c. and d.c. is the simplest form of system towards interconnection. In a system, insertion of only one d.c. link will form this system. It does not involve much cost also as would be necessary to convert whole of the existing system into d.c. one.
2. Two a.c. systems which have different frequencies can be interconnected by means of a d.c. tie line, as d.c. tie line is asynchronous link. So frequency difference does not matter here.
3. It is seen from power flow characteristic of a parallel system that if a d.c. link is inserted in parallel with a.c. link, the power received at the receiving end is increased highly. Table below gives a comparative study of maximum power transmitted for different types of systems.

Comparision of different system

Type of system	Maxm. Power Transmitted
Single Circuit a.c. system	0.66 p.u.
Double Circuit a.c. System	1.02 p.u.
A.C./D.C. parallel system	3.046 p.u.

It is obvious that parallel (combined) a.c. d.c. system will increase steady state power limit to a much higher level. This much increase in power level was not possible by a.c. single or double circuit system.

4. Under transient conditions, the effective control of d.c. power flow can be employed to raise stability limit. This is because of the fact that d.c. power can be changed more promptly simply by exercising the control of firing angles. It is also noted that greater the initial d.c. power, more improvement in stability is observed.

5. In a.c. interconnected system, the fault current increases as number of interconnections increase. But if a d.c. link is introduced in the neighbourhood, the fault current is reduced. This reduction in fault current is proportional to the loading of d.c. line.

C O N C L U S I O N E S

CONCLUSIONS

In the work done, an attempt has been made to discuss some important aspects of d.c. transmission. A brief summary of background and present status of the problem has been given. A method based on the theory given by Dr. T.Horigome of Electrotechnical Laboratory, Japan ,to analyse the d.c. system, has been adopted. A parallel a.c. and d.c. system has been considered and analytical equations have been derived for such a system.

The reactive power requirements of inverters vary with load conditions and system parameters. Effect of various system parameters on reactive power demand has been studied and it has been found that for light loads at high power factor, reactive power is not considerable and can be easily met by the system,but when inverters have to be rated for large power and load has a poor power factor, considerable amount of reactive power is needed for successful system operation.

Different methods to meet the reactive power demand already in use, have been discussed for comparative study and suitability under different circumstances. D.C. power flow has been studied under different conditions. A parallel a.c. and d.c. system has been taken as an example and its power angle characteristics have been calculated. The results obtained are of vital importance because it is seen therefrom that when an a.c. line is paralleled by a d.c. line, the power transmission capacity of a system is increased. Limiting ratio of a.c. and d.c. power for stability has been calculated and it is observed that in a parallel system a.c. takes only a small portion of load whereas d.c. line shares a major portion of load.

Stability studies have shown that steady state power level is increased highly by paralleling a.c. line with d.c. line, but the limiting value of torque angle is less than 90°. Effect of presence of d.c. link has been carried out. In a system, fault current increases as the number of a.c. interconnections increases. If interconnection is made by using a d.c. link, then for fault at the load, the a.c. fault current is reduced. This reduction is proportional to the loading of d.c. line (i.e. larger load d.c. line shares more is the reduction in a.c. fault current). Therefore considerable improvement in stability is expected.

Stability of inverter has also been discussed and it is found that for successful operation of inverter there should be adequate supply, of reactive power as well as inverter firing angle β should not fall below a certain value of angle, required to deionise a valve.

Studies made here are important from the point of view that these show the results in favour of possible use of a parallel a.c. and d.c. system.

REFERENCES

1. Adamson, C. and Hingorani N.G.

"High Voltage Direct Current Power Transmission" (Book), Garraway, London, 1960.

2. Feinberg R., Hingorani N.G.

"Basic Theory of Operation and Control of a h.v.d.c. Power Transmission System and its Implementation in a system Analyser". Proc. I.E.E. London, March, 1962, Monograph No. 5098.

3. Gavrilovic A., Taylor.

"Calculation of Regulation Characteristics of D.C. Transmission System" Power Apparatus & System, March, 1964, P. 215.

4. Horigome T., Ito. H.

"Analytical Research for Power Systems Containing D.C. Transmission Links". Bulletin of Electrotechnical Laboratory Japan, Vol. 26,5(1962).

5. Horigome T. & Ito. H.

" Analysis of D.C.Transmission(A Book), Programming Research Seri s(2) of Japan, Government.

6. Hingorani N.G.

"A suggested Cource on h.v.d.c. Transmission, Part I" International Journal of Electrical Engineering Education (1964).

7. Part II of above., 1964 PP. 393-405.

8. Part III of above., 1964 PP. 37-49.

. Hingorani N.G.,

"Use of Capacitors for Reduction of Commutation Angle in Static High Power Converters" Proc. I.E.E. December, 19_5, P. 2333-2341.

10. Ito H. & Adamson C.

"Fault Level and Stability of an A.C.D.C. Parallel Operating System"
Direct Current, November, 1964, pp. 128-135.

11. Ito, H.

"Analytical Research for Power System Containing D.C.Transmission Link Part-2"
Bulletin of Electrotechnical Laboratory, Japan
Vol. 26,8,(1962).

12. Kimbark, E.W.,

"Power System Stability(Book)"

13. Machida T.,

"Improving Transient Stability of A.C.System by Joint Usage of D.C.System"
I.E.E.E. International Conventional Record
Part 9, (1965), pp. 37-44.

14. Peterson, Reitan and Phadke.

"Parallel Operation of A.C/D.C. Power Systems"
Power Apparatus & Systems, January, 1965, pp. 15.

15. Stevenson, W.D.

"Power System ~~Stability~~ Analysis (Book)".

16. U.S.S.R. Direct Current Research(A Book), 1964.
Pergamon Press, London.