Commutation in Invertors under Steady-State and Transient Conditions

A Dissertation
submitted in partial fulfilment
of the requirements for the Degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(Advanced Electrical Machines)

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ROORKEE
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* CERTIFICATE *

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Certified that the dissertation entitled

" Commutation in Invertors under Steady-State and Transient Conditions "

which is being submitted by Sri MAHENDRA PRASAD in partial fulfilment for the award of the Degree of Master of Engineering in "Advanced Electrical Machines" 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 7 months from January to July '68 for preparing dissertation for Master of Engineering Degree at the University.

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Dated October 17 ,1968

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A C K N O W L E D G E M E N T

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Last but not the least, the author expresses his sincere thanks to Mr. H.Bhaumic for his suggestions and encouragement.

CONTENTS

SYNOPSIS

For stable operation of an invertor, a certain amount of reactive power is necessary. The amount of reactive power depends mainly upon the overlap angle γ . As a matter of fact, this overlap angle is affected by various system parameters and load conditions.

In this dissertation, the effect of various system parameters and load conditions on reactive power demand has been studied. It also deals with the use of capacitors and filter circuits for reduction of commutation angle and hence the reactive power consumption. Relative advantages and disadvantages have been assessed. Different aspects of commutation failure and protection against it has been discussed. The effect of faults on the a.c. side on the reactive power demand has been studied. The variation of current in an invertor under different transient situation has been analysed. In each case a suitable example has been assumed and analysed.

S Y M B O L S

Unless otherwise stated, following notations will be used:

E = r.m.s. voltage between phases of the transformer.

e = e.m.f. on d.c. side.

E_1, E_2, E_3 = r.m.s. voltages between the phases of the transformer secondary corresponding to r.m.s. voltages between R-Y, Y-B, B-R respectively.

e_1, e_2, e_3 = instantaneous voltages corresponding to E_1, E_2 and E_3 respectively.

E_d, V_d = D.C. line voltage.

V_o = output d.c.voltage on no load with $\alpha = o$

E_L = Load voltage.

U_{fwd} = Forward voltage-drop in a valve

I = r.m.s. value of the transformer secondary current.

I_d = d.c. line current.

i_1, i_2, i_3 = instantaneous currents in a commutation circuit through electromagnetic and electric induction respectively.

i_S = instantaneous short-circuit current.

i = Transient current

i(n) = Transient current at n^{th} interval.

i(o) = output current at the ~~ob~~ start of the transient process.

L = leakage inductance of a convertor.

L_F = inductance in a filter circuit.

P = General symbol for power rating

P_c = Rating of power factor correcting capacitor.

P_o = System short-circuit capacity.

P_r = reactive-power on the a.c. side.

P_a = active-power.

X_C	=	commutation reactance of one phase.
X	=	Transformer reactance (Chapter 2) inductive reactance of a reactor (Chapter 5).
X_γ	=	inductive reactance upon which commutation angle γ mainly depends.
r	=	Transformer resistance.
C	=	Capacitance of the filter-circuit.
A	=	Active component of load power.
R	=	Reactive component of load-power.
α	=	delay angle of valve firing of a valve.
β	=	Advance angle of valve-firing of an invertor at the start of transient process.
β_n	=	Advance angle of valve firing of an invertor at the n^{th} interval in transient process.
γ	=	angle of commutation or angle of overlap.
γ_o	=	angle of commutation of at zero angle of delay
γ^1	=	resultant commutation angle.
δ	=	angle between the voltage zero and the end of commutation of an invertor.
δ_o	=	deionization angle.
θ_o	=	instant at which transient process starts.
θ_n	=	instant corresponding to n^{th} interval.
ϕ	=	power-factor angle.
ϕ^1	=	lagging power-factor angle of an invertor.
ϕ_L	=	load power-factor angle.
p	=	phase number
n	=	order of harmonics (Chapter 4), intervals 1,2,3, 4,5 etc. (Chapter 5).
ΔV	=	d.c.voltage drop due to commutation.

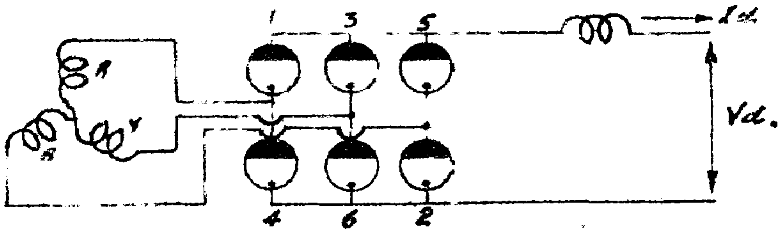
I N T R O D U C T I O N

With increased demand of power at distant places, it was necessary to raise the transmission voltage. This can be met with h.v.a.c. or h.v.d.c. transmission. D.C. transmission has its main application where distances are large and where power has to be transmitted in bulk form from one place to another and it is advantageous when a water barrier, has to be crossed. In d.c. there is no easy way of transformation of voltage as in a.c. For this reason, a.c. has been universally accepted for distribution. Voltage can be stepped up on the a.c. side of the converting station. In the case of h.v.d.c.transmission, a.c. - d.c. static power convertor during normal operation can be controlled to allow power flow in either direction. The convertor operating as an invertor allows power flow from d.c. to a.c. and the case is reversed with rectifier. The d.c. side of the convertor can supply only active power whereas the a.c. side supplies both active power and reactive power. When the convertor is operating as an invertor, it operates at a leading power factor, and requires reactive power for satisfactory operation. The reactive power demand is not much under normal range of operation, but it increases rapidly as the load increases or if power factor falls. Faults on the a.c. side decrease the a.c. voltage and increases the direct current thereby increasing the commutation angle which results in an increased demand of reactive power. Under such conditions, invertor operation will not be possible if precautionry measures are not taken to meet the reactive power demand. To overcome any such difficulty, appreciable reduction in commutation angle and consequently saving in reactive power demand can be obtained by connecting static capacitors (or synchronous condenser depending upon convertor rating) to the secondary winding of the convertor transformer. In most large power station, capacitors are replaced by capacitive filter circuits. Filter circuits filter harmonics present in the alternating current.

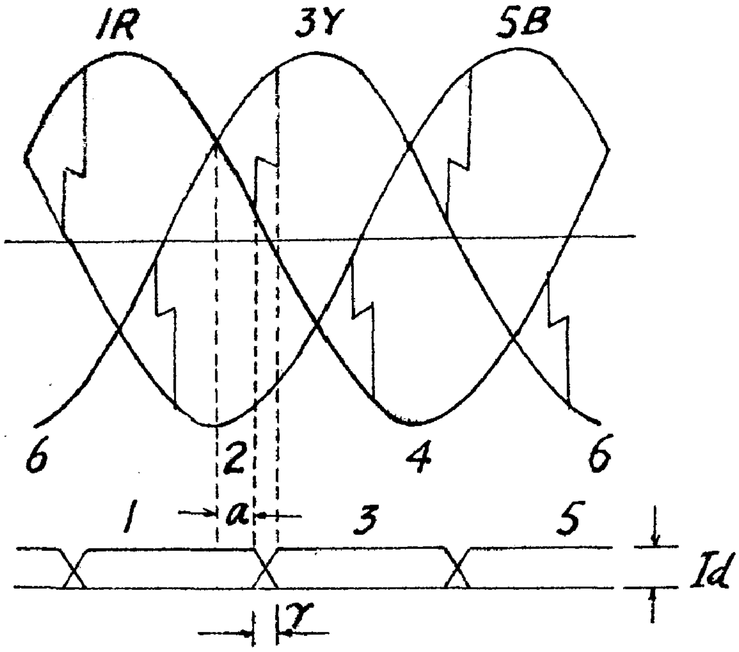
In analysing transient behaviour, method of difference equation has been adopted, because an invertor has discretely and periodically varying parameters. The method has been applied to study the nature of quantities under transient conditions.

The present study brings about the possibility of connecting filter circuits rather than static capacitor directly across the transformer secondary winding, where they are electrically adjacent to the convertor. It also includes the analysis of output current under transient conditions due to possible disturbances.

CHAPTER - 1 (Ref. 1,2,3,4,7)



(a) BRIDGE CONNECTION



D.C. VOLTAGE AND CURRENT WAVE-FORMS, WHEN TRANSFORMER WINDING REACTANCE AND FIRING ANGLE OF VALVES ARE BEING CONSIDERED

FIG. 1.1 - OPERATION OF A BRIDGE CONVERTOR

1.2. OPERATION OF A BRIDGE CONVERTER (Ref. 2,4):-

In the case of convertor, three types of valve arrangements can be adopted, out of which the bridge connection makes the best utilisation of the transformer. A three-phase bridge connection shown in the Fig.(1.1a) has been accepted universally, as the best connection for h.v.d.c. convertors because this connection not only provides the best utilisation of transformer but also it includes the effects due to grid control and transformer winding reactances. Fig.(1.1b) represents the current and voltage waveforms and the thick line represents the direct voltage.

In the operation of rectifier, grid control is provided to control the output voltage. If α is the delay angle, then the conversion -relation is given by:

$$Vd = \frac{3\sqrt{2}}{\pi} \cdot E \cos\alpha = Vo \cos\alpha \ .$$

where,

E = r.m.s. secondary voltage between phases

α = grid control angle.

Vd = Direct voltage

Vo = Average value of the output voltage.

When one valve stops conducting and other valve starts, the current can neither suddenly drop to zero in previous value nor attain its full value Id immediately after firing in the later valve. But it takes some finite time α, known as overlap angle or commutation angle, for current either to drop to zero or to reach its full value Id. This overlap causes reduction in the direct voltage.

In the figure shown, the grid control and transformer winding reactance (i.e. α and X) have been taken into account. When valve 3 fires at the point P, valve 3 takes over conduction from valve 1 due to commutation. This firing of valve 3 results in short circuit between the phases Y and R. The increasing short circuit current opposes the forward current Id in valve 1 until it reduces to zero. At the same time it increases the direct current in valve 3 to full valve Id. The equation of this short circuit current is given by;

$$2L \frac{di_s}{dt} = \sqrt{2}\ E \sin Wt.$$

where, L = leakage inductance of one phase of transformer.

i_s = instantaneous short circuit current.

After integrating between the limits:

when $Wt = \alpha$, $i_s = o$,

& $Wt = \alpha + \gamma$, i_s = Id,

the solution is given by

$$Id = \frac{E}{\sqrt{2}\ WL} \left\{ \cos\alpha - \cos(\alpha + \gamma) \right\}$$

By integrating and arranging the voltage waveform, the average output voltage relation is given by the following expression:

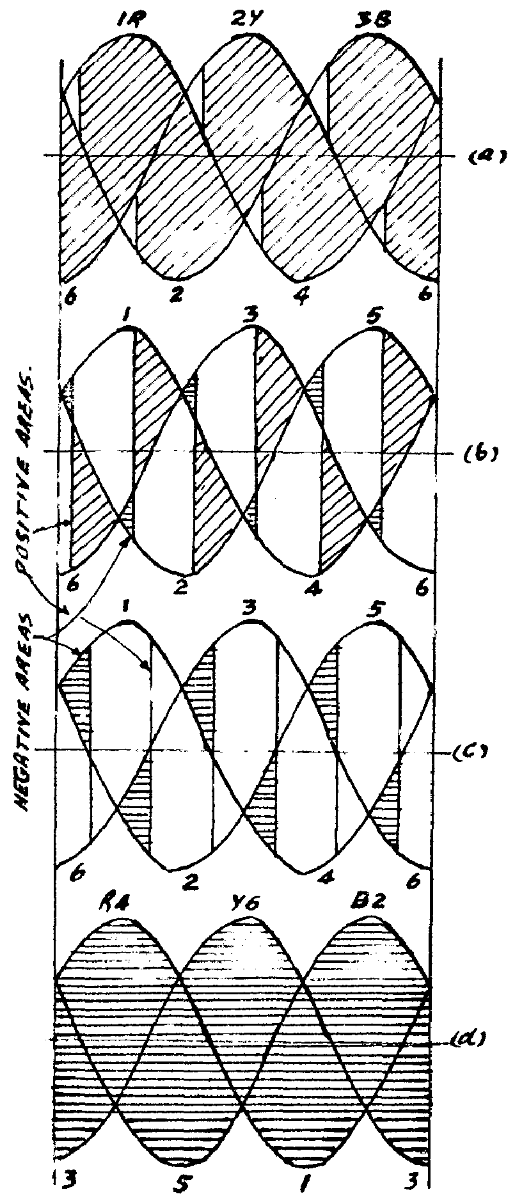
$$Vd = \frac{3\sqrt{2}\ E}{\pi} \quad \frac{\cos\alpha + \cos(\alpha + \gamma)}{2}$$

If the commutation angle γ is neglected, then,

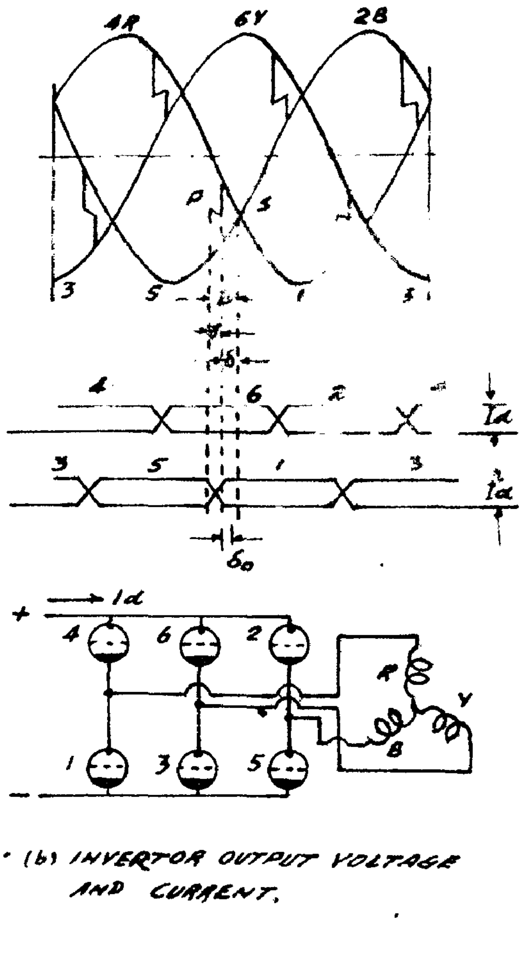
$$Vd = \frac{3\sqrt{2}}{\pi}\ E \cos\alpha = Vo \cos\alpha .$$

where,

Vo = max. no load output voltage with $\alpha = o$.



(a) OPERATION OF AN INVERTOR.



(b) INVERTOR OUTPUT VOLTAGE AND CURRENT.

FIG.1.2

1.3. OPERATION OF AN INVERTOR (Ref. 1,2,3,4,7):-

Fig. 1.2 (a & b):

We know that when bridge unit works as a rectifier and if the commutation angle is neglected,

$$Vd = V_0 \cos \alpha$$

From Fig.(1.2) we see that when the control angle α is increased beyond 60^o there is some negative voltage.

At $\alpha = 90^o$, the positive an negative voltages are equal and consequently the average voltage is zero.

At $\alpha = 180^o$, the -ve voltage is equal to the +ve voltage for rectifier with $\alpha = o$.

Also, mathematically,

$$Vd = V_0 \cos 180^o = - V_0.$$

Now, if d.c. voltage is applied from some external source, which is sufficient to overcome this negative area and forces the current, then the current flows in opposition to the induced e.m.f. i.e. it flows from anode to the cathode. It indicates that the power is supplied to the a.c. system. Under such circumstances the rectifier becomes invertor.

It is important to note that the current is still flowing in the same direction, forced by the rectifier voltage. Then the firing angle is known as the angle of advance firing and is given by

$$\alpha = \pi - \beta$$

The conversion of electrical energy follows the principle of transformer if the current flows in the direction of the induced e.m.f., then there is a release of energy and the process is of rectification. But if the current flows in opposite direction to that of the induced e.m.f. then there is acceptance of energy and this process is known as inversion

It is clear from the Fig.(1.4) that the commutation from the valve 5 to the valve 1 must be completed before the point S. Actually angle γ accounts for the completion of the commutation for that particular pair of valves and so is left for valve 5 to deionise. This angle δ_o is necessary to stop the further conduction of valve 5. Thus the valve 1 is fired at the point P, an angle β before the point S. For the invertor operation, the grid control is essential because the valve 1 is prevented from firing upto the point P by negative bias on its grid.

In the case of rectifier operation, there is always some delay in valve firing in order to control the output voltage and also finite time is required for commutation to be completed, therefore, in this case the convertor operation at lagging p.f. and the power flows from a.c. to d.c. In case of inversion, the firing must be done in advance for commutation and deionisation to be completed well before the voltage is zero, therefore in this case the convertor operates at leading p.f. For rectification due to small angle of delay, the reactive power consumed is small or negligible. But in case of invertor, reactive power supply is required in order to run it on leading p.f. During steady state, the reactive power required may be 40 to 50 percent of the real power, but during transients, the reactive power required may be upto 75% of the real power. The a.c. system may not be able to supply that much of reactive power, therefore, to serve for this purpose special provisions are made in form of static capacitors, or synchronous condenser. When the convertor rating is less than 1/5th of the system capacity, static capacitors are used, otherwise synchronous condensers are used.

1.4. VALVE CONNECTIONS (Ref.3,7):-

The maximum valve rating at present in case of mercury arc valves is below 200 KV. Therefore, H.V.D.C. terminal stations may require more than one valve. In contradiction to universal practice of parallel connection of valves in case of a.c. stations, nowadays there is general tendency to connect the valves in series where a d.c. terminal station requires more than one valve. This is done in order to facilitate taking 'out' and 'in' of the valves in case if some fault is developed. A by-pass valve may also be connected across d.c. terminals to facilitate putting 'in' or 'out' of a particular valve in the circuit.

CHAPTER - 2 (Ref. 1,4,5,6,11)

" Variation of reactive power demand with system parameters and load conditions"

2.1. NEED OF REACTIVE POWER:

A.C. - D.C. static power converters are used in many applications such as in variable speed drive in rolling machines and high voltage direct current transmission scheme. A converter can be operated as a rectifier or as an inverter depending upon the requirements. The grid control action in converter makes it possible to supply power in either direction. Irrespective of the direction of power flow, the d.c. side of the convertor can supply only active power whereas the a.c. side supplies both active as well as reactive power. The consumption of reactive power in a convertor makes the requirement of reactive power quite essential for stable operation.

When operating as a rectifier, there is always some delay in valve firing in order to control the output voltage and also finite time is required for commutation to be completed, therefore in this case the convertor operates at lagging p.f. Also power flows from a.c. to d.c. In rectification, due to small angle of delay, the reactive power consumed is very small if not neglected. Therefore, in this case the reactive power together with the active power is supplied by the a.c. system itself.

When operating as an invertor, the power flows from d.c. to a.c. The firing must be done in advance for commutation and deionisation to get completed well before the voltage zero. Therefore the invertor can be treated as operating at a leading p.f. Therefore, the reactive power in this case is large. Thus the invertor is equivalent to a generator working on leading p.f. and which can supply only active power. Therefore, it needs some reactive power in order to the requirements of reactive power.

During steady state the reactive power required may be 40 to 50% of the real power, but during transients, the reactive power required may be upto 75% of the real power. The a.c. system may not be able to supply that much of reactive power, therefore to serve for this purpose, special provisions are made in terms of static capacitors, or synchronous condensors. When the convertor rating is less than 1/5th of the system capacity, static capacitors are used, otherwise synchronous condensors are more suited.

2.2. GENERAL EXPRESSIONS FOR REACTIVE POWER:-

The relation between the alternating and direct current is given by,

$$I = \frac{\sqrt{6}}{\pi} Id$$

D.C. output voltage developed by the invertor is

$$Vd = \frac{3\sqrt{2}}{\pi} E \frac{\cos B + \cos\delta}{2} = V_o \left(\frac{\cos B + \cos\delta}{2}\right)$$

Equating d.c. and a.c. powers

$$\sqrt{3}EI \cos\phi = \frac{3\sqrt{2}}{\pi} E \frac{\cos B + \cos\delta}{2} . I_d$$

$$\text{or,} \quad \sqrt{3}E \frac{\sqrt{6}}{\pi} Id \cos\phi = \frac{3\sqrt{2}}{\pi} E \frac{\cos B + \cos\delta}{2} . I_d$$

$$\text{or} \quad \cos\phi = \frac{\cos B + \cos\delta}{2}$$

A.C. apparent power is given by

$$P = \sqrt{3} . EI = V_o Id.$$

Active power (which is d.c. power also)

$$P(a) = V_0 \, Id \, \text{Cos}\,\phi = V_0 \, Id \, \frac{\text{Cos}\,\beta + \text{Cos}\,\delta}{2}$$

Therefore, reactive power is found as

$$P(r) = \sqrt{P^2 - P^2(a)} = V_0 \, Id \, \text{Sin}\,\phi.$$

where, $\text{Sin}\,\phi = \text{Sin}\left[\text{Cos}^{-1} \frac{\text{Cos}\,\beta + \text{Cos}\,\delta}{2}\right]$

Also,

$$Id = \frac{E}{\sqrt{2}\;WL}\,(\text{Cos}\,\delta - \text{Cos}\,\beta)$$

Substituting for Id,

$$Pr = \frac{3E^2}{\pi WL}\,(\text{Cos}\,\delta - \text{Cos}\,\beta)\,\text{Sin}\left[\text{Cos}^{-1}\frac{\text{Cos}\,\delta + \text{Cos}\,\beta}{2}\right]$$

Also, from the relation

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

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

$$\therefore\; Pr = \frac{3E^2}{\pi WL} \times (\text{Cos}\,\delta - \text{Cos}\,\beta)\,\text{Sin}\,(\text{Cos}^{-1}\,\text{Cos}\,\phi)$$

$$= \frac{2 \times 3E^2}{\pi WL}\,(\text{Cos}\,\delta - \text{Cos}\,\phi)\,\text{Sin}\,\phi \qquad (2.1)$$

$$= \frac{6\,E^2}{\pi WL}\,(\text{Cos}\,\delta - \text{Cos}\,\phi)\,\text{Sin}\,\phi \qquad (2.1)$$

2.3. Reactive power under different load conditions:-

Let,

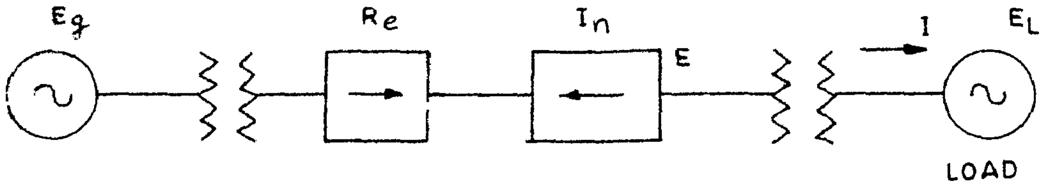
E_L = load voltage = constant

ϕ = power factor at inverter end

ϕ_L = load power factor

R = Transformer resistance which can be neglecte

X = Transformer reactance.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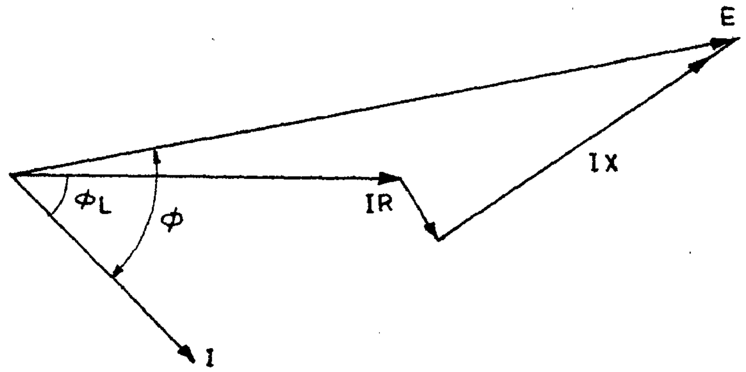
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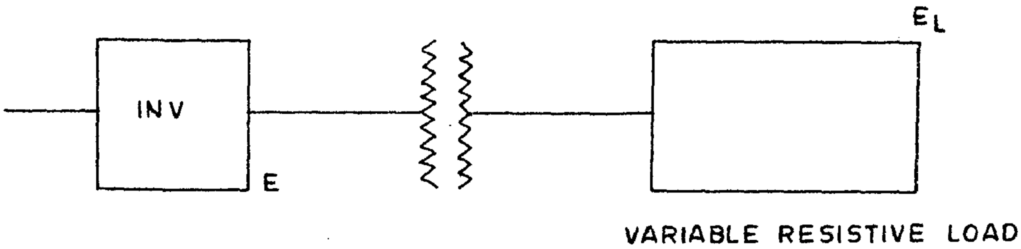
EL
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E
VARIABLE RESISTIVE LOAD

FIG. 2.1

Let the reactance and resistance of the transmission line is neglected. This depends upon the fact that the load is situated at the secondary of the transformer. The diagram is as shown. in fig. 2.1.

Let, load power is $= A + jR$

where, A = Active component

& R = Reactive component

therefore,

$$\phi_L = \tan^{-1} \frac{R}{A}.$$

Also, from the vector diagram.

$$\tan \phi = \frac{E_L \sin \phi_L + IX}{E_L \cos \phi_L + I.r}.$$

If r is neglected then,

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

2.3(a) <u>Case I</u>:-

(a) Pure resistive load (i.e. $R = o$,)

Then, $\sin \phi_L = 0$, $\cos \phi_L = 1$

$$\tan \phi = \frac{IX}{E_L} \qquad (2.2)$$

and $E = E_L + jI.X.$ (2.3)

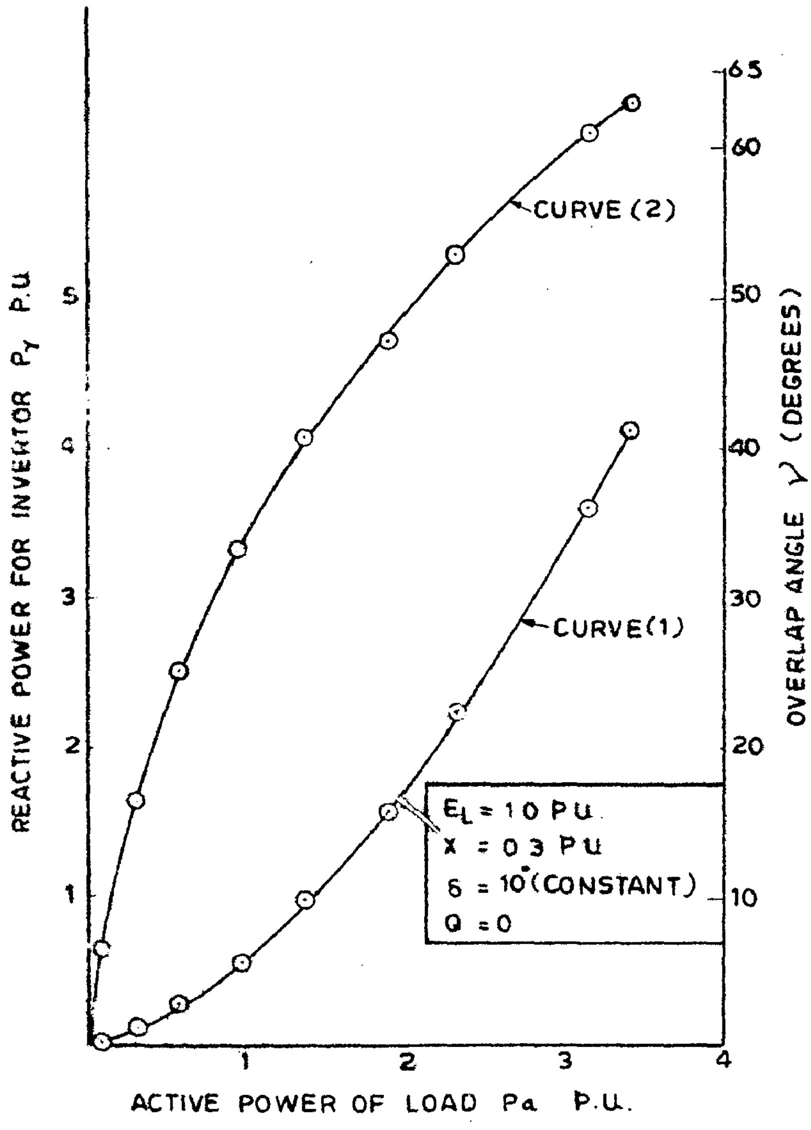
The quantity $\frac{IX}{E_L}$ represents the percentage reactance of transformer.

<u>EXAMPLE</u>:

Let, $E_L = 1$ p.u.

$X = 0.3$ p.u.

$\delta = \delta_o = 10^o =$ const.



[illegible] VARIATION OF REACTIVE POWER FOR INVERTOR AND OVERLAP ANGLE WITH ACTIVE POWER OF LOAD (PURE RESISTIVE LOAD)

Let load be purely resistive, so that the load reactive power = Q = o

$$\cos \delta_o = 0.985$$

ϕ and E are found from equations (2.2) and (2.3) for different loads. Then Pr is found from the eqn. (2.1). The commutation angle γ is found from the following relation

$$2 \cos \phi - \cos \delta = \cos (\delta + \gamma)$$

Calculations have been done and shown in the Tables 2.1 and 2.2 respectively.

2.3(b) Case 2:-

Now, we calculate the variation of reactive power with load power factor.

The power factor at the invertor end is given by,

$$\tan \phi = \frac{E_L \sin \phi_L + IX}{E_L \cos \phi_L} \qquad (2.4)$$

(neglecting the resistance of the transformer).

Load power factor,

$$\phi_L = \tan^{-1} \frac{R}{A}$$

R = Reactive Power

A = Active power

Substituting ϕ_L in (2.4), we get,

$$\tan \phi = \frac{E_L \sin (\tan^{-1} \frac{R}{A}) + IX}{E_L \cos (\tan^{-1} \frac{R}{A})} \quad - (2.5)$$

As discussed previously, reactive power required is given by,

$$Pr = \frac{6E^2}{\pi WL} (\cos \delta - \cos \phi) \sin \phi$$

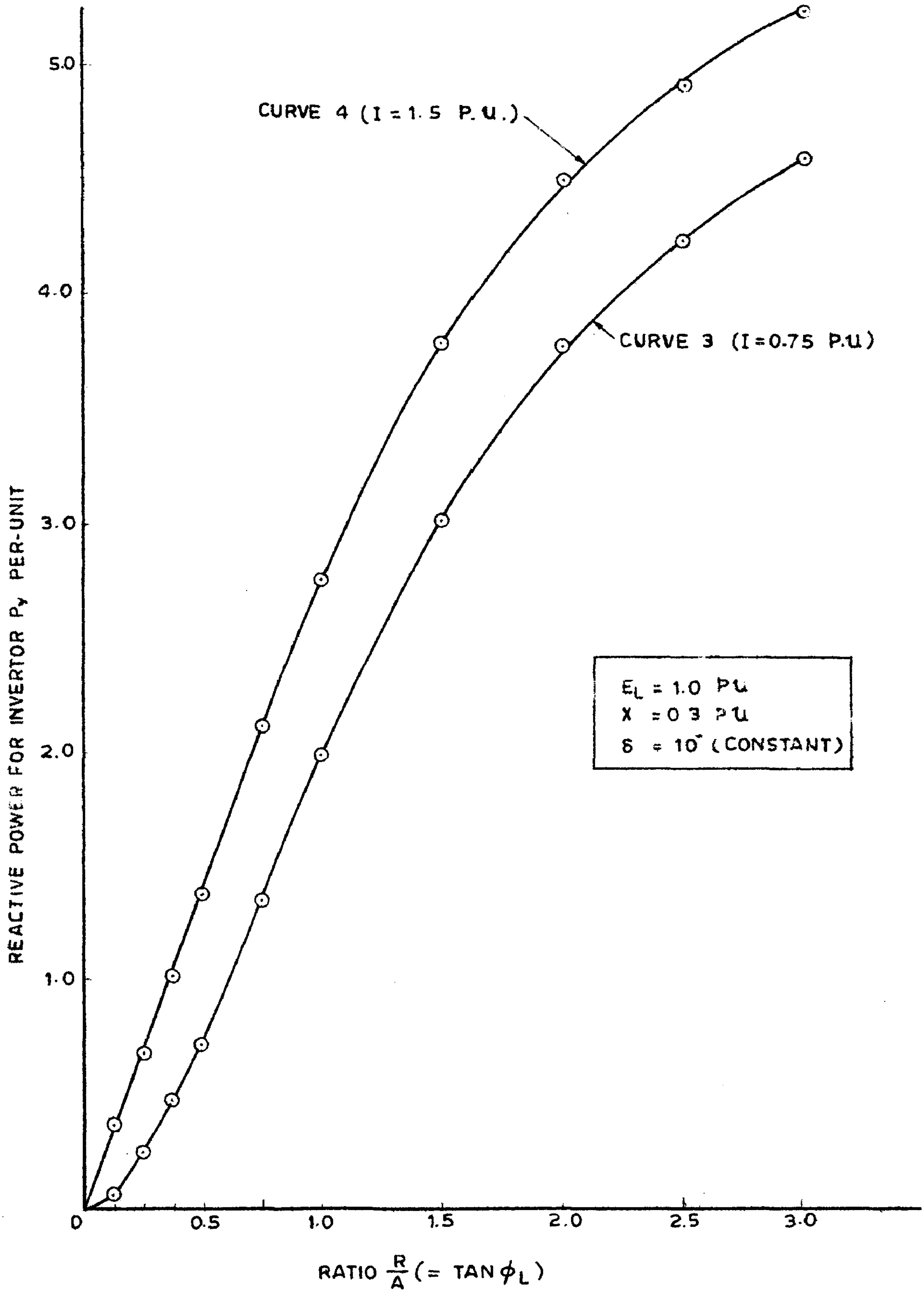


FIG. 2·3-VARIATION OF REACTIVE POWER WITH LOAD POWER FACTOR

<u>EXAMPLE</u> :- We take the previous figure with the same parameters.

In this case reactive power will be calculated for a particular value of current and different load power factors.

For different $\frac{R}{A}$, ϕ is calculated from (2.5) and thence cos ϕ and Sin ϕ. Thereafter, Pr is calculated for two values of currents.

$I = 0.75$ p.u. & $I = 1.5$ p.u.

Calculations have been shown in Tables 2.3 and 2.4 for I = 0.75 p.u. and 1.5 p.u. respectively.

$$E = E_L + \dot{J}IX$$

For $I = 0.75$ p.u.

$$E = 1.00 + \dot{J}\ 0.75 \times 0.3$$

$$= 1.00 + \dot{J}\ 0.225$$

$$\therefore E^2 = 1.025$$

For, $I = 1.5$ p.u.

$$E = 1.00 + J \times 1.5 \times 0.3$$

$$= 1.00 + J\ 0.45$$

$$\therefore E^2 = 1.1$$

For $I = 0.75$ p.u

$$\frac{6E^2}{\pi \times 0.3} = \frac{6 \times 1.025}{\pi \times 0.3} = 6.54$$

For $I = 1.5$ p.u

$$\frac{6E^2}{\pi \times 0.3} = \frac{6 \times 1.1}{\pi \times 0.3} = +7.0$$

2.4. CONCLUSIONS:-

Figures 2.2 and 2.3 give idea about the variation of reactive power required for invertor operation under different conditions of loads.

Curve (1) shows the variation of invertor reactive power with active power of load, when load p.f. is zero. Curves (3) and (4) show the variation of reactive power required by the invertor with load power factor. Curve (2) shows the relation between active power of load and invertor overlap angle.

From curves (1), when active power consumed by the load is increased, it causes increase in current drawn from the invertor. This increase in current drawn is responsible for the increase in overlap angle, as indicated by curve (2). This increase in overlap angle increases the reactive power required by the invertor. In other words, as shown in curve (1) that for purely resistive load, the reactive power required for invertor operation is not constant, but it increases with the active power consumed by the load.

Curve (1) shows that under normal range of operation the demand of reactive power is not much. As the load increases, the reactive power demand also increases and at higher values of active load, the curve becomes more steep, and therefore it becomes uneconomical to supply reactive power at such a high rate. However, at extremely high values of load, the invertor may fail to operate and therefore under normal range of operation, it is not difficult to meet the reactive power demand.

Curves (3) and (4) which show the variation of reactive power demand for invertor with load p.f. for two values of load currents, (for 0.75 p.u. & 1.5 p.u respectively), indicate that when the load power factoris poor, the load will comparatively require more reactive power. This is because, the reactance of the load will increase the overlap angle of the invertor. High p.f. reduces the demand for reactive power for inversion and hence resistive loads can be more conveniently supplied by the invertor.

Curves (3) and (4) also show that high load current leads to larger consumption of reactive power.

In general, we can conclude that invertor needs a considerable amount of reactive power for its operation. In all cases of loads, the reactive power demand is not high under normal range of operation but it rapidly increases, as the load is increased or if power factor falls. Therefore, to avoid troubles, it is necessary to take precautions to meet the reactive power demand.

	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.8	4.0
$\tan \phi = \frac{I.X}{E_L}$	0.12	0.24	0.36	0.48	0.6	0.72	0.84	0.96	1.14	1.2
ϕ	6.83	13.5	19.8	25.6	31	35.75	40	43.8	48.8	50.2
$\cos \phi$	0.994	0.972	0.940	0.902	0.856	0.811	0.765	0.721	0.658	0.64
$0.985-\cos \phi$	-0.009	0.013	0.045	0.083	0.129	0.174	0.220	0.264	0.327	0.345
$\sin \phi$	0.119	0.233	0.3385	0.432	0.515	0.584	0.643	0.692	0.752	0.768
E_2	1.006	1.027	1.062	1.11	1.165	1.23	1.306	1.384	1.515	1.56
E^2	1.0144	1.0576	1.13	1.23	1.36	1.52	1.707	1.92	2.3	2.44
P_r (Reactive power p.u.)	0.00692	0.0204	0.1095	0.282	0.586	0.985	1.597	2.235	3.61	4.12
P_a (Active power p.u)	0.0577	0.0851	0.304	0.59	0.975	1.37	1.9	2.325	3.16	3.44

Table 2.1

VARIATION OF REACTIVE POWER DEMAND OF INVERTOR WITH ACTIVE POWER OF LOAD

2 Cos Ø	1.998	1.944	1.880	1.804	1.712	1.622	1.530	1.442	1.316	1.280
2 Cos Ø - Cos δ = Cos($\delta+\gamma$)		0.959	0.895	0.819	0.727	0.637	0.545	0.457	0.331	0.295
$\delta+\gamma$		16.5	26.3	35	43.4	50.4	57	62.8	70.7	72.83
$\therefore\ \gamma$		6.5	16.3	25	33.4	40.4	47	52.8	60.7	62.83

Table 2.2

VARIATION OF OVERLAP-ANGLE WITH ACTIVE POWER OF LOAD

$\tan \phi_L = \frac{R}{A}$	0.125	0.25	0.375	0.5	0.75	1.0	1.5	2.0	2.5	3.0
$\therefore \phi_L =$	5.84	14	20.5	26.5	36.8	45.0	56.4	63.5	68.2	71.6
$\sin \phi_L$	0.102	0.242	0.35	0.446	0.6	0.707	0.831	0.895	0.93	0.95
$\cos \phi_L$	0.995	0.97	0.935	0.895	0.8	0.707	0.554	0.446	0.371	0.316
$\tan \phi$	0.3285	0.482	0.615	0.75	1.03	1.32	1.91	2.513	3.12	3.72
ϕ	18.15	25.7	31.55	36.83	46	52.85	62.3	68.6	72.4	74.96
$\sin \phi = B$	0.3115	0.434	0.522	0.6	0.72	0.796	0.885	0.93	0.954	0.965
$\cos \phi$	0.95	0.9	0.851	0.8	0.695	0.603	0.465	0.365	0.306	0.259
$0.985 - \cos \phi = A$	0.35	0.085	0.134	0.185	0.29	0.382	0.520	0.620	0.679	0.726
$P_r = 6.54\ A.B$ For $I = 0.75$ p.u	0.0713	0.241	0.456	0.725	1.365	1.99	3.01	3.77	4.225	4.58

Table 2.3

VARIATION OF REACTIVE POWER DEMAND OF INVERTOR WITH RATIO $\frac{R}{A}$ OF LOAD

($I = 0.75$ p.u.)

At $\phi_L \neq 0$.

$\tan \phi_L = \frac{R}{A}$	0.125	0.25	0.375	0.5	0.75	1.0	1.5	2.0	2.5	3.0
$\therefore \phi_L$	5.83	14	20.5	26.5	36.8	45	56.4	63.5	68.2	71.6
$\sin \phi_L$	0.102	0.242	0.35	0.446	0.6	0.707	0.831	0.895	0.93	0.95
$\cos \phi_L$	0.995	0.97	0.935	0.895	0.8	0.707	0.554	0.446	0.371	0.316
$\tan \phi$	0.555	0.713	0.855	1.0	1.313	1.637	2.32	3.02	3.72	4.43
$\therefore \phi$	29	35.4	40.51	45	52.72	58.51	66.7	72.7	75.0	77.3
$\cos \phi$	0.875	0.815	0.76	0.707	0.605	0.522	0.396	0.297	0.2597	0.222
$0.985 - \cos \phi = A$	0.110	0.170	0.225	0.278	0.380	0.463	0.589	0.688	0.726	0.763
$\sin \phi = B$	0.485	0.58	0.65	0.707	0.795	0.853	0.917	0.954	0.965	0.975
Pr(p.u) = 7.0 AB for I=1.5 p.u	0.3735	0.69	1.023	1.376	2.12	2.77	3.78	4.6	4.9	5.21

Table 2.4

VARIATION OF REACTIVE POWER DEMAND OF INVERTOR WITH RATIO $\frac{R}{A}$ OF THE LOAD

(I = 1.5 p.u)

CHAPTER - 3 (Ref. 1, 8)

" Commutation failure and reactive-power demand in case of faults on the a.c.system "

3.1. <u>Commutation failure</u>:-

The inverter faults can be categarised as follows depending upon the nature of faults:-

1. Commutation failure.
2. Fire through or grid blocking failure.
3. Arc quenching and failure of a valve to fire.
4. Inverter backfire

The most severe inverter fault is ~~to-be~~ the commutation failure, which will be discussed in details.

3.2. <u>Commutation failure</u> :- Commutation failure occurs generally due to:

i) Reduction in d.c. voltage during commutation process.

ii) Excitation failure.

These faults can be very greatly reduced by proper compounding of the invertor.

Figure 3.1 shows how commutation failure (single commutation failure, double commutation failure) occurs due to reduction in a.c. voltage or due to less deterioration period. At the point A, where the valve 3 has fired, commutation is expected to take place. From valve 1 to 3, it is supposed that commutation is not able to take place due to any of the above reasons. Under such conditions the anode voltage of 1 becomes positive w.r.t. that of 3. Therefore after the pt. B valve 3 stops and valve 1 conducts together with valve 2. After B, the back voltage, which is voltages between phases R and B, is less than the value

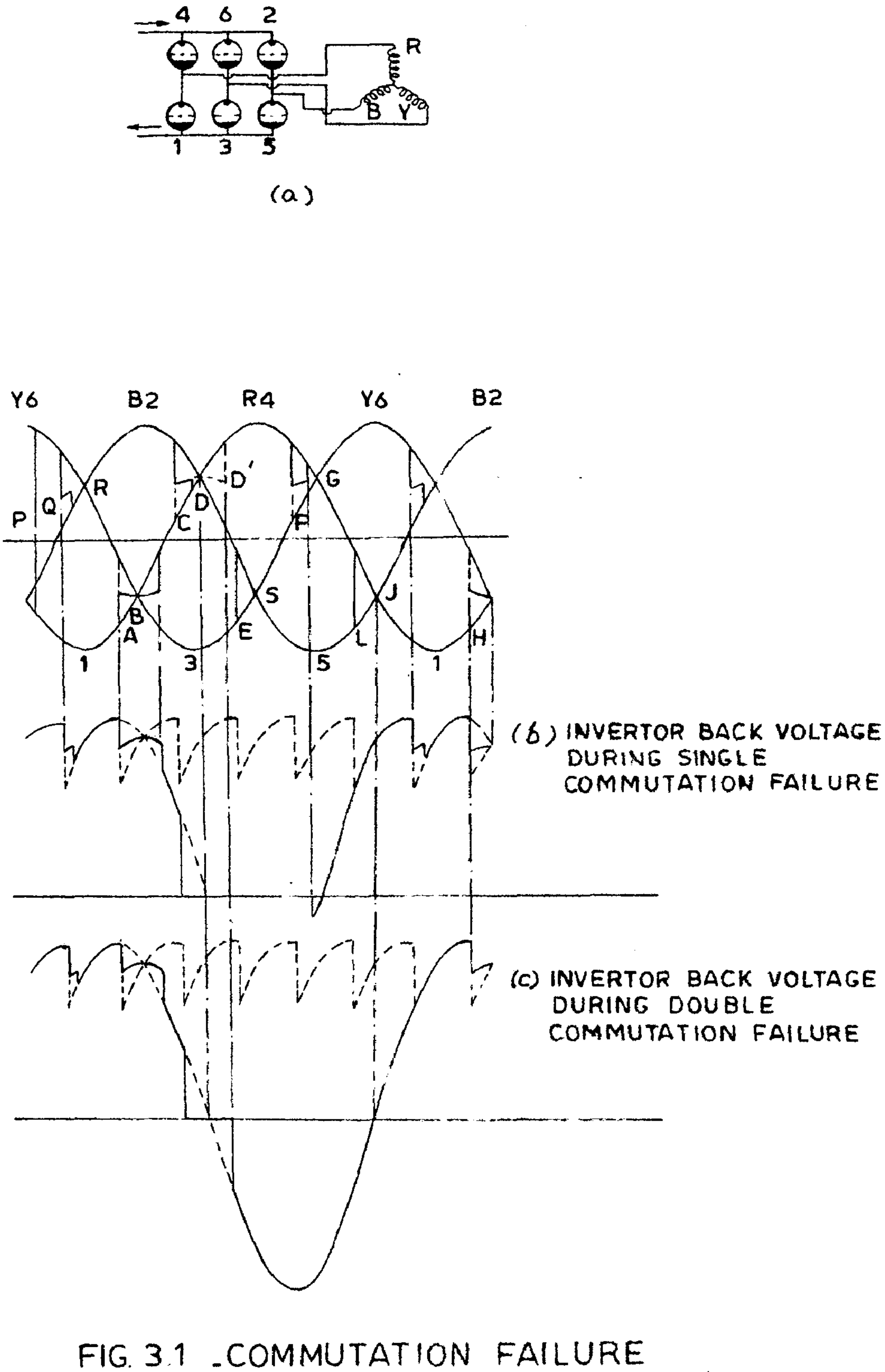


FIG. 3.1 .COMMUTATION FAILURE

which should have been in absence of above reasons. At C valve 4 fires and commutation takes place from 2 to 4. Thus after the Pt. C, valves 1 & 4 conduct together and d.c. short-circuit results. Therefore, the short circuit current does not pass through the transformer wdgs. after the point C. At the point E, where the anode voltage of 5 is negative w.r.t. that of conducting valve 1, nothing happens when 5 fires. At the point F, current commutation from 4 to 6. Between F and G, the back voltage becomes negative. After the point G, the back voltage establishes itself and short circuit is over. At the point H, commutation is expeded from valve 1 to the valve 3 and then the normal operation continues without much disturbance.

The current rise between the point B and C, which is not great because of the transformer inductance and smoothing choke, may be sufficient to cause a commutation failure of valve 4 from 2. (Figures (a) and (c)). This results in still more severe conditions, because after the point D, the voltage between the phases B and R reverses and then the a.c. voltage is no more back voltage, but it adds up with the d.c. Under such conditions a severe short-circuit of the d.c. and a.c. voltages through the transformer winding results. Hence the inverter becomes a rectifier in series with a rectifier.

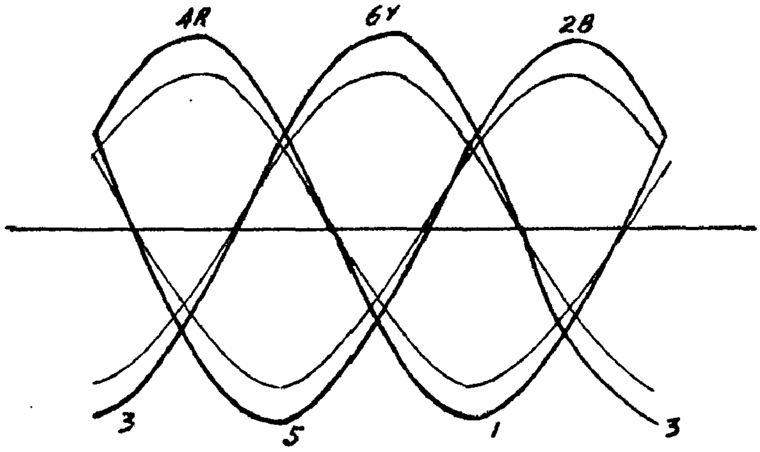
Under such severe conditions, at points E, F and I nothing happens due to firing of respective valves because the anode voltage of firing valves is negative than that of those from which commutation is to take place. At the point J, the a.c. back voltage becomes positive and establishes thereafter. At H commutation from 1 to 3 takes place and normal operation is expected thereafter.

In case of double commutation failure only a part of d.c. passes through a pair of valves. In this case C D becomes the commutation time from valve 2 to 4 and back. The current passing through the pair of valves, by-passes the transformer winding for the interval C D. When double commutation failure becomes of permanent nature, the only remedy is blocking of the invertor valves and opening of the by-pass valves. In case of correctly compounded invertor, if such type of failure occurs at all, the invertor may even recover from such a fault. It is to be noted that the short circuit by-passes the a.c. windings for 120 in a single commutation failure and for the interval CD in double commutation failure.

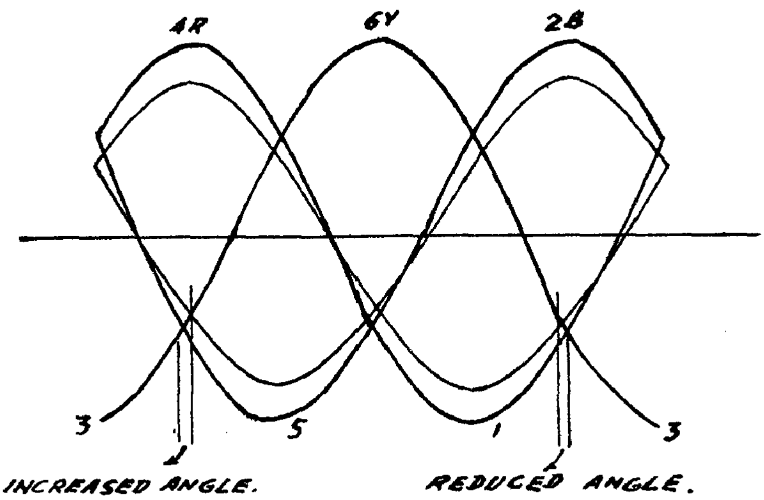
3.3. Protection against commutation failure:-

1. By properly compounding the invertor these faults are very greatly reduced.

2. By using a relay which compares a.c. and d.c. currents, the a.c. current being rectified, since the short circuit current by-passes the transformer windings for a longer period in case of single commutation failure then that of in case of double commutation failure, therefore for every commutation failure, the d.c. will exceed a.c. If this happens for two successive cycles, the invertor can be blocked by a suitable arrangement. This is a good method because in this case, the invertor can recover



(a) THREE PHASE FAULT.



(b) TWO PHASE FAULT.

FIG 3.2. CHANGES IN COMMUTATION ANGLE AND VOLTAGE DUE TO REDUCTION IN THE INVERTOR A.C. VOLTAGES its normal state automatically.

3. In case of severe faults, the inverter is blocked by the opening of its valve and then unblocked after about five cycles. This short time of interruption will have little effect on the receiving a.c. system.

4. By providing a large angle β during normal operation; By doing so, some safe limit of voltage reduction can be provided so that upto that limit, the commutation is still completed by an angle δ_0 before the change of voltage sign. Therefore, no commutation failure takes place for a considerable reduction in voltage on a.c. side.

3.4. Reactive power requirement under conditions of faults:-

Reactive power demand depends mainly upon the commutation angle. From Fig. 3.2, it is clear that faults on the a.c.side decrease the a.c. voltage and increase the direct current, thereby increasing the commutation-angle. Hence the faults on the a.c.side affect the reactive power demand required by the invertor seriously. During faults, the firing angle β will increase automatically in compounded invertor. This cannot be so in the uncompounded invertor. Hence a large angle β is to be provided in case of uncompounded invertor for stable operation, which needs more reactive power. Therefore, it is better to analyse reactive power demand under the conditions of faults for both compounded as well as uncompounded invertors separately.

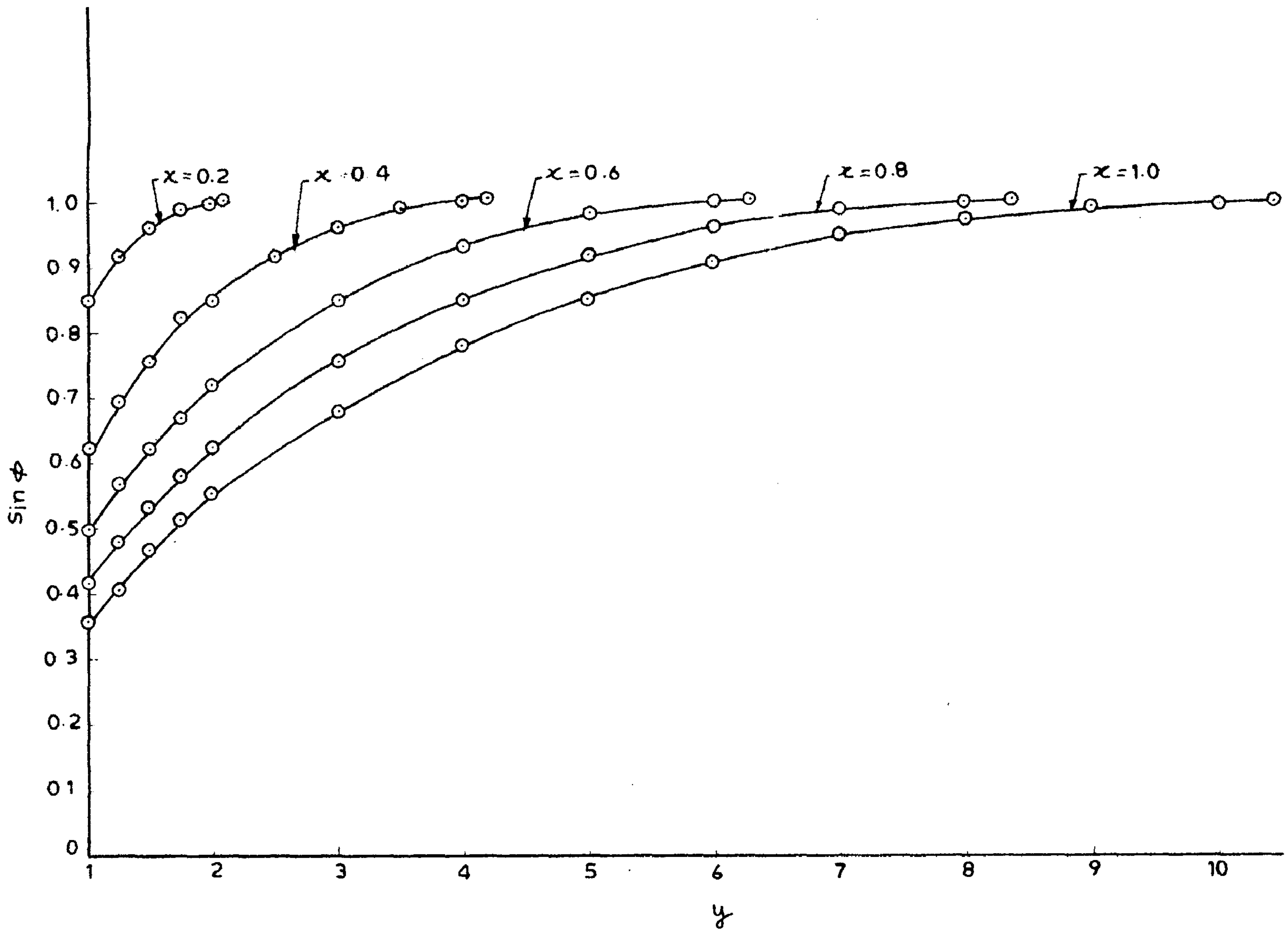


FIG. 3.3 - EFFECT OF FAULTS ON THE A.C. SIDE ON INVERTOR REACTIVE POWER CONSUMPTION (UNCOMPOUNDED INVERTOR) $\delta = 10°$ CONSTANT $\frac{\Delta V}{V_o} = 0.05$

Let a stable operation is required during fault when a.c. voltage decreases from E to χE and the direct current increases from I_d to γI_d. For this the angle δ should be at least δ_0.

The leading power factor of the invertor is given by

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

Let $\frac{\Delta V}{V_o}$ is the inductive voltage regulation due to commutation process.

Then it can be shown (Ref. 1) that:

$$\text{Cos}\,\phi = \text{Cos}\,\delta_0 - \frac{\Delta V}{V_o}\left(\frac{2\gamma}{\chi} - 1\right) \quad \text{for uncompounded invertor}$$

&

$$\text{Cos}\,\phi = \text{Cos}\,\delta_0 - \frac{\Delta V}{V_o}\,\frac{\gamma}{\chi} \quad \text{for compounded invertor.}$$

<u>Example</u> :- It is better to illustrate the reactive power demand under fault conditions by an example.

Let $\frac{\Delta V}{V_o}$ = 0.05,

$\delta = \delta_0 = 10^{\circ}$

χ = 0.2, 0.4, 0.6, 0.8, and 1.0

γ = 1.0, 1.25, 1.5, 1.75, & 2.0, 3.0, 4.0, 5.0 etc.

For these values of $\frac{\Delta V}{V_o}$, δ_0 and different sets of χ and γ, we determine Cos ϕ from the above equations for both compounded and uncompounded inverters ~~are determined~~. Then tan ϕ, as can be determined from Cos ϕ, will give the ratio of reactive power to the active power. The results obtained are shown in the following Tables. The value of Sin ϕ will

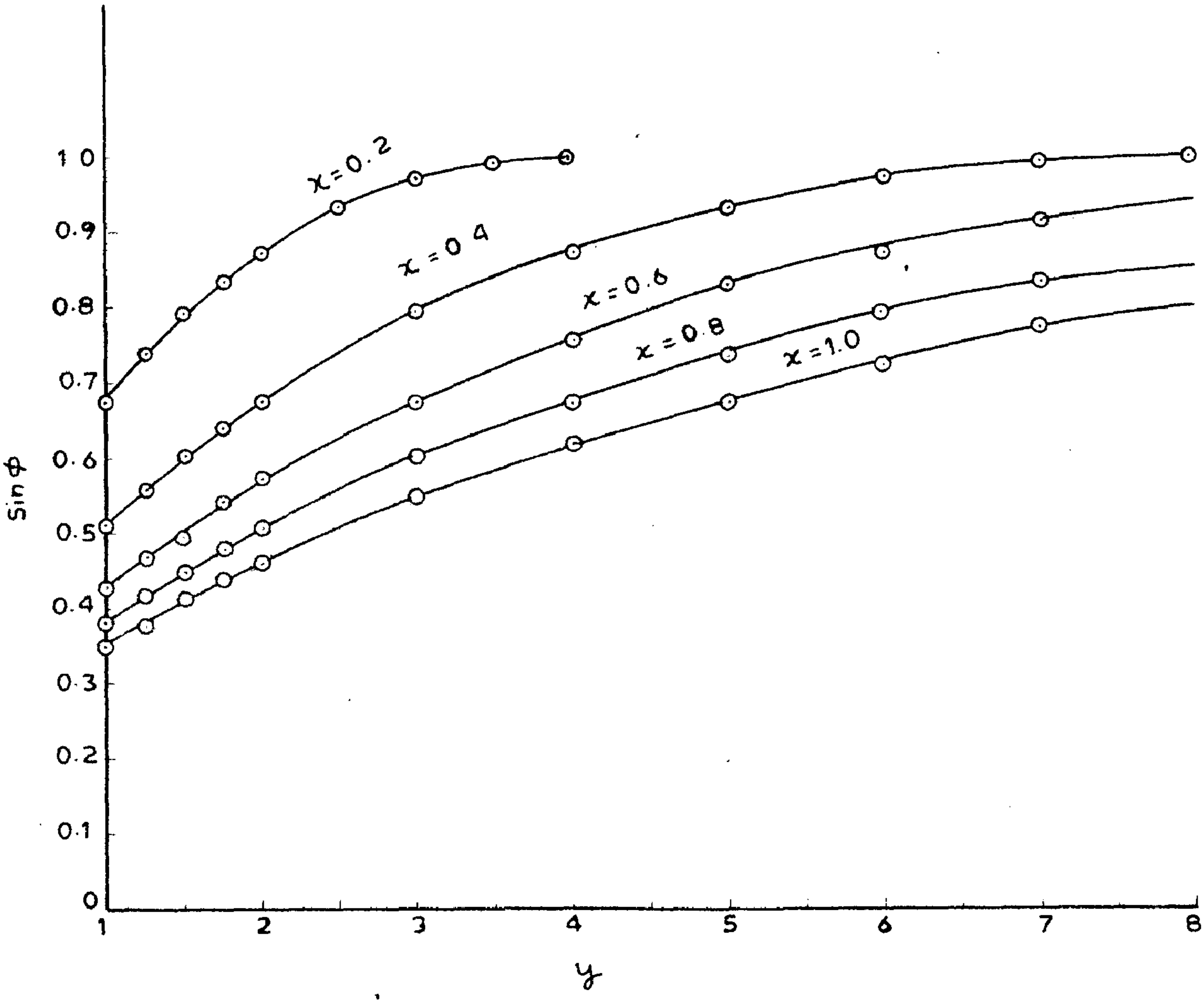


FIG. 3.4 .EFFECT OF FAULTS ON THE A.C. SIDE ON INVERTOR REACTIVE POWER CONSUMPTION (COMPOUNDED INVERTOR) $\delta = 10^{\circ}$ = CONSTANT, $\frac{\Delta V}{V_0} = 0.05$

give the ratio of the reactive power required to the KVA rating. Figures 3.3 and 3.4 show relationship between X and Sin ϕ for uncompounded and compounded invertors respectively.

For uncompounded Invertor $\frac{\Delta V}{V_o} = 0.05$, $\delta = \delta_o = 10^\circ$

x	y	Sin ø
0.2	1.0	0.844
	1.25	0.912
	1.5	0.9585
	1.75	0.98715
	2.0	0.9999
	2.09	1.0
0.4	1.0	0.62
	1.25	0.69
	1.50	0.75
	1.75	0.82
	2.0	0.845
	2.5	0.912
	3.0	0.9585
	3.5	0.9871
	4.0	0.999
	4.18	1.00
0.6	1.0	0.497
	1.25	0.564
	1.50	0.62
	1.75	0.666
	2.0	0.711
	3.0	0.844
	4.0	0.929
	5.0	0.9787
	6.0	0.999
	6.27	1.00
0.8	1.0	0.415
	1.25	0.475
	1.50	0.53
	1.75	0.578
	2.0	0.62
	3.0	0.7505
	4.5	0.844
	5.0	0.912
	6.0	0.9585
	7.0	0.9871
	8.0	0.999
	8.36	1.00
1.0	1.0	0.355
	1.25	0.4
	1.50	0.462
	1.75	0.51
	2.0	0.55
	3.0	0.677
	4.0	0.773
	5.0	0.844
	6.0	0.9005
	7.0	0.942

	8.0	0.972
	9.0	0.9908
	10.0	0.999
	10.45	1.00

For compounded Invertors $\frac{\triangle V}{V_o} = 0.05,\ \delta = \delta_o = 10^o$

0.2	1.0	0.677
	1.25	0.74
	1.50	0.7925
	1.75	0.836
	2.0	0.874
	2.5	0.933
	3.0	0.972
	3.5	0.9939
	3.98	1.00
0.4	1.0	0.51
	1.25	0.56
	1.50	0.605
	1.75	0.642
	2.0	0.677
	3.0	0.7925
	4.0	0.874
	5.0	0.933
	6.0	0.972
	7.0	0.9939
	7.96	1.00
0.6	1.0	0.43
	1.25	0.47
	1.50	0.496
	1.75	0.545
	2.0	0.575
	3.0	0.678
	4.0	0.758
	5.0	0.834
	6.0	0.874
	7.0	0.9156
	11.9	1.00
0.8	1.0	0.385
	1.25	0.42
	1.50	0.45
	1.75	0.481
	2.0	0.51
	3.0	0.603
	4.0	0.678
	5.0	0.74
	6.0	0.7925
	7.0	0.836
	15.92	1.00

	1.0	0.355
	1.25	0.383
1.0	1.50	0.415
	1.75	0.44
	2.0	0.465
	3.0	0.55
	4.0	0.62
	5.0	0.678
	6.0	0.728
	7.0	0.772
	19-9	1.00

<u>CHAPTER - 4</u> (Ref.1,2,4,5,6,7,12)

" Reduction of commutation angle and saving in reactive-power demand by connecting static capacitors or filter circuits on the transformer secondary windings "

4.1. NECESSITY OF REDUCTION OF COMMUTATION ANGLE:-

The reactive power consumed by the invertor during its operation is considerable which may not be obtainable from the a.c. system itself. Even with an angle of advance automatically maintained at the minimum for safe commutation, as is done in h.v.d.c. convertors, the reactive power requirements may be as much as 50 - 60% of the power transmitted. Therefore, some special provisions must be made locally so as to reduce the reactive power consumed by the invertor.

The reactive power required by the invertor is given by the equation:

$$P_r = \frac{6E^2}{\pi W L_2} \left[\cos\delta - \cos(\delta + \gamma) \right] \sin\left[\cos^{-1} \frac{\cos\delta + \cos(\delta + \gamma)}{2} \right.$$

From the above equation, it is seen that if δ remain constant, then reactive power required mainly depends upon the overlap angle γ . Then angle γ is responsible for variation of reactive power demand for inversion. It is also seen that if γ is reduced, then reactive power required is less. Therefore by controlling the angle γ ,we can have desired value of reactive power consumed. Before going to various means of controlling the overlap angle γ , it is desirable to investigate the effect of various system parameters on this angle.

4.2. VARIATION OF OVERLAP ANGLE:-

Overlap angle depends primarily on the following factors:

1) Voltage at invertor transformer secondary

2) Load power factor

3) Reactance of transformer

4) Load current

5) A.C. system faults

Thus the changes in any of the above quantities is responsible for variation of commutation angle. Below it is discussed briefly how the above factors affect the commutation angle:

1) Voltage at the invertor Transformer Secondary:-

From the figure 3.2 it is seen that due to reduction in the invertor a.c. voltage, there are changes in commutation angle and voltage. If direct voltage is to remain constant, then the whole effect results in sufficient variation in commutation angle Analytically:

$$E_d = \frac{3\sqrt{2}}{\pi} E \frac{\cos\delta + \cos(\delta + \gamma)}{2}$$

If direct voltage at invertor end is constant, the overlap angle is increased due to reduction in transformer secondary voltage.

2) Reactance (Leakage) of Transformer:-

The following relation stands valid for transformer reactance and the alternating voltage:

$$WL = \frac{E}{\sqrt{2}\, I_d} \left[\cos\delta - \cos(\delta + \gamma) \right]$$

From the above relation it is seen that if E, I_d and δ are constant, then an increase in the transformer leakage reactance results in an increase in the overlap angle.

3) Load power factor:-

It has already been shown in Chapter 2, that

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

It is seen from above that a high load power factor tends to decrease the angle ϕ i.e. effect is to decrease the overlap angle and hence reactive power demand is less.

4) Load current:-

Overlap angle and direct current are related by the following equation:

$$I_d = \frac{E_2}{\sqrt{2}\ wL_2} \left[\cos \delta - \cos (\delta + \gamma) \right]$$

It is clear from above that increasing current increases the overlap angle and hence for stable operation of invertor more and more reactive power is required.

5) A.C. system faults:-

In general, the faults on a.c. system cause either reduction or collapse of voltage. From Fig. 3.2, it is seen that due to three phase or two phase faults, the voltage available for commutation is decreased which in turn increases the overlap angle.

Symmetrical reduction in three - phase voltages occurs only during three-phase faults. However, unbalanced faults on the a.c. side result in phase displacement as well as voltage reduction. In this case voltage reduction will be lower than in the case of three-phase faults. Commutation.

failure,which is result of A.C. system fault, will be dealt with later on.

4.3. REDUCTION OF COMMUTATION ANGLE:-

Efforts to reduce reactive power consumed by reducing commutation-angle are being done since as early as 1942. These efforts are based upon the fact that by connecting static capacitors or filter circuits to the invertor transformer, the direct current changes, which results in reduction of commutation angle thereby saving in reactive power demand. Usual practice to obtain saving in reactive power i.e. reduction in commutation angle is to connect static capacitors or filters on the primary side (i.e. line side) of the invertor transformer or alternatively a tertiary winding is provided, specially for static capacitors. If however, these filters or static capacitors are connected to valve side (i.e. on secondary side of the invertor transformer), the capacitor discharge would assist commutation resulting in reduced commutation angle, thus allowing the invertor to operate at an improved power factor. By so doing, the invertor reactive power consumption and generated harmonics are counteracted as near their source as possible and no longer flow through the transformer. It should be noted, however, that methods to reduce reactive power demand are still in experimental stage, so the discussion made below will give an idea about the improvement in commutation angle. The discussion made will not weight up the advantages and disadvantages in terms of hard cash, but the advantages may considerably outweigh the disadvantages.

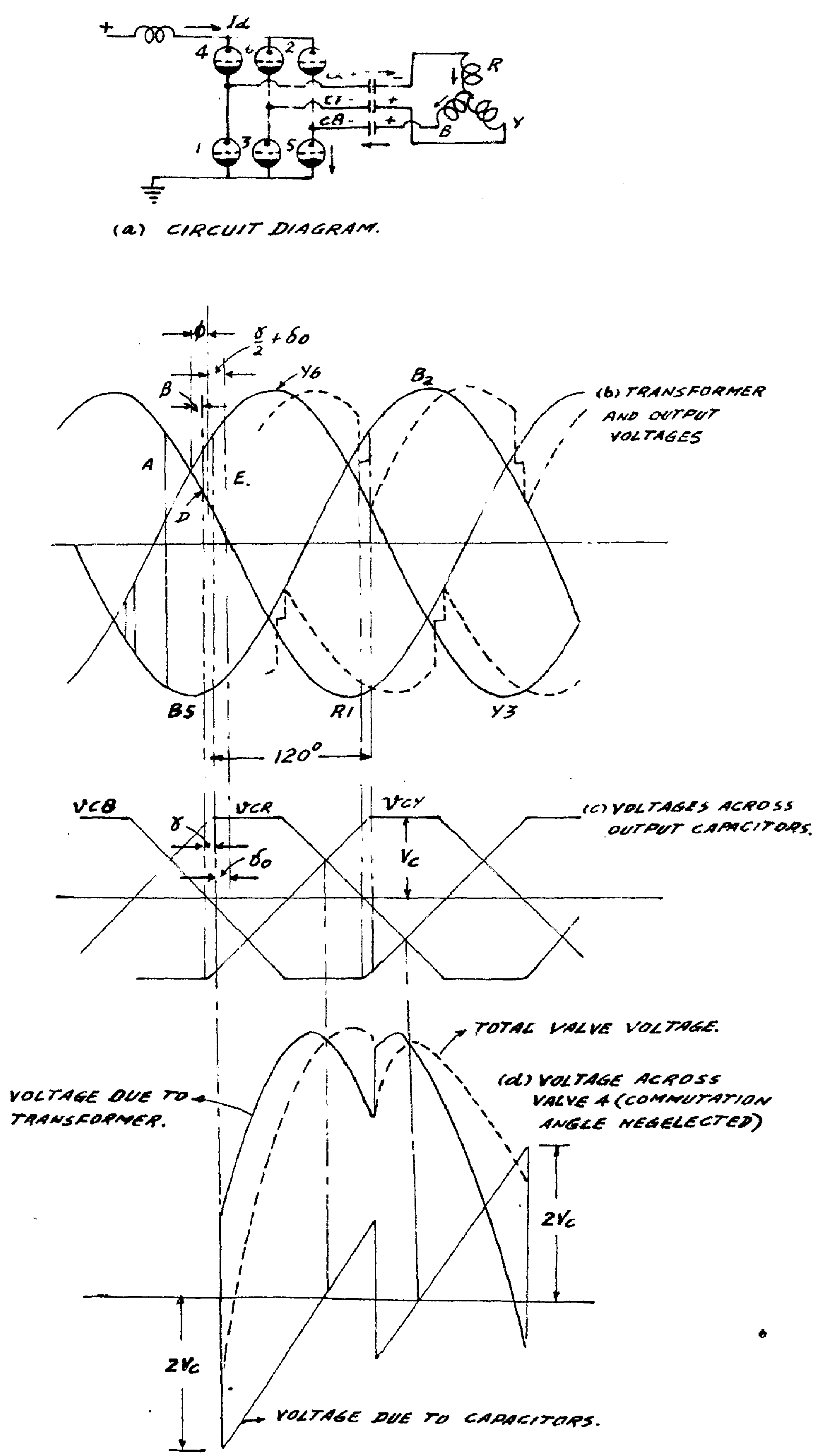


FIG. 4.1 INVERTOR WITH SERIES CAPACITORS IN THE TRANSFORMER SECONDARY

4.4. IMPROVEMENT IN COMMUTATION ANGLE USING SERIES CAPACITORS IN THE TRANSFORMER SECONDARY WINDINGS:

This method, which is the simplest and the best of the methods available for improving commutation angle by artificial means, consists of connecting capacitors in shunt or series fashion on the transformer secondary (Fig.4.1). In our case we consider series capacitors in the transformer secondary windings. This method depends upon the fact that when two valves of different phases (say 4 and 5 of phases R 4 Y respectively) are conducting through the phases R 4 Y, then one of the capacitors (C_R in our case) is charged in positive direction, other one (C_B) is charged in negative direction and the third one (i.e. C_Y) is maintained in a charged state at a negative voltage and the voltages across these capacitors, which depend upon the magnitude of the current, are superimposed upon the voltage between the cathodes of the two valves between which commutation is commencing. To make the picture more clear, let commutation is to take from valve 4 to valve 6. This is only possible of the voltage between the cathodes of 4 and 6 is positive i.e. cathode of 4 is positive w.r.t. the cathode of 6. At some point, when the voltage e_1 between the phases R and Y may be negative, the voltage between the cathodes of 4 and 6 remain positive due to superimposed positive voltage of the capacitors i.e. due to superposition of V_{CR} & V_{CY}. Thus the voltage between cathodes of 4 & 6 is equal to $V_{CR} + V_{CY} - e_1$ and remains positive so long as $e_1 < V_{CR} + V_{CY}$.

This voltage $V_{CR} + V_{CY}$ remains approximately constant during the commutation period and after that it starts to decrease. The deionisation, therefore, must be completed before $V_{CR} + V_{CY} - e_1$ becomes negative. Thus with sufficient capacitor voltages, the commutation angle may be reduced appreciably.

It should be noted that the capacitor voltage, which depends upon the magnitude of the current, may not be sufficient at reduced currents. Therefore the capacitor voltage at normal currents should be sufficiently high so that it can give enough voltage at reduced currents for the same power factor. This is what is required in this process. If this requirement is not fulfilled, then the power factor at lower currents will have to be reduced which results in increased reactive power demand.

For successful completion of commutation and deionisation, (Ref. 1)

$$V_{CR} + V_{CY} > e_1$$

$$\text{or} \quad 2\,V_C - 2\,V_C \frac{\delta o + \gamma/2}{120} > \sqrt{2}\ E\ \text{Sin}\,(\phi' + \frac{\gamma}{2} - \delta o) \quad - (4.1)$$

$$\& \quad \frac{\gamma}{2} = \frac{18000.L.\ Id}{2\,V_C\,(1 - \frac{\gamma/2}{120}) - \sqrt{2}\ E\ \text{Sin}\,\phi'} \quad - (4.2)$$

<u>EXAMPLE</u> :- In this example, we show relation between direct current Id and the corresponding commutation angle γ for safe commutation assuming other parameters and then find the relation between the same quantities when capacitors are not used i.e. for natural commutation. The comparision of both results will show that there is sufficient improve-

-ment in commutation angle by the use of capacitors.

Let $V_o = 1$ p.u., $\therefore E = \frac{\pi}{3\sqrt{2}} V_o = \frac{\pi}{3\sqrt{2}} \cdot 1 = 0.74$ p.u.

$L = 0.1$ p.u.

$\cos\phi = 0.995 \quad \therefore \phi = 5.75^\circ$

$V_C = 0.3$ p.u. for $Id = 1.0$ p.u

$\delta_o = 10^\circ =$ constant.

γ is found out from the relation (4.2), for different values of Id so long relation (4.1) is satisfied. The calculation here are presented in Table (4.1):

I_d p.u	1.00	0.95	0.9	0.85	0.8	0.75	0.7	0.65
V_C	0.3	.285	.27	.255	.24	.225	.21	.195
$\gamma/2$	3.78	3.83	3.88	3.94	4.00	4.08	4.19	4.31
γ°	7.56	7.66	7.76	7.88	8.00	8.16	8.38	8.62
$V_{CR}+V_{CY}$	.532	.505	.4780	.4500	.424	.395	.37	.344
e_1	.35	.351	.3518	.3524	.3534	.354	.357	.368
$V_{CR}+V_{CY}-e_1$	.182	.154	.1162	.0976	.0706	.041	.013	-.024

Table 4.1

It is clear from the above table that the relation (4.1) is not satisfied for Id less than 0.7 p.u. The reason is that the capacitor voltage, which directly depends upon the current Id, is not sufficient for safe commutation. Here power factor throughout is kept at a value of 0.995. In this connection we see that the capacitor voltage at normal currents should be sufficiently high to give enough voltage at reduced currents for the same power factor

For natural commutation, (Ref. 1)

$$I_d = \frac{E}{\sqrt{2}\,WL}\left[\cos(\beta - \gamma) - \cos\beta\right]$$

or

$$I_d = \frac{E}{\sqrt{2}\,WL}\left[\cos\delta - \cos\beta\right]$$

or

$$I_d = \frac{E}{\sqrt{2}\,WL}\left[0.985 - \cos\beta\right]$$

For same parameters, the overlap angle γ is calculated for I_d varying from 1.00 p.u. to 0.7 p.u and for natural commutation as shown in Table 4.2:

Id	1.00	.95	.90	.85	.80	.75	0.7
.985-Cos β	.191	.181	.172	.162	.153	.143	.133
Cos β	.794	.804	.813	.823	.832	.842	.8514
β	37.5	36.5	35.5	34.55	33.6	32.5	31.5
γ	27.5°	26.5	25.5	24.55	23.6	22.5	21.5

Table 4.2

For stable operation, as discussed, at the most:

$$\sqrt{2}\,E \sin\left(\phi + \frac{\gamma}{2} - \delta_o\right) = 2\,V_C\left[1 - \frac{\delta_o + \frac{\gamma}{2}}{120}\right]$$ in case of secondary connected static capacitors.

For $Id = 0.7$ p.u., $\frac{\gamma}{2} = 4.19^\circ = 4.19^\circ$.

For stable operation, at the most, $\sqrt{2}\, E \sin(\phi' + \frac{\gamma}{2} - \delta_o) = .3$

$$1.412 \times 0.72 \sin(\phi' + 4.19 - 10) = 0.37$$

$$\text{or} \quad \sin(\phi' + 4.19 - 10) = \frac{0.37}{1.412 \times 0.72} = 0.3635$$

$$\text{i.e.} \sin(\phi' + 4.19 - 10) = 0.3635.$$

$$\therefore \phi' + 4.19 - 10 = 21.3^\circ$$

$$\phi \text{ or } \phi' = 31.3 - 4.19 = 27.11$$

$\therefore$ Power factor $= \cos\phi' = 0.89$

This is the minimum power factor of the system in this example in case of secondary connected static capacitors for stable operation.

Thus, the reduction in reactive power is mainly because of the fact, that the static capacitors will improve power factor of the system thereby reducing the overlap angle.

In figure (4.4), curves (b) and (a) show the relationship between I_d and γ for the artificial commutation and for natural commutation respectively. By comparing them, it is clear that the overlap angle can be reduced appreciably by the use of static capacitors in transformer secondaries.

4.5. MERITS: -

(1) Static capacitors are cheaper, have small losses and low cost of operation.

(2) Better utilization of installed capacity is achieved because of improved power factor.

(3) Due to high capacitor voltage, in case of large capacity of static capacitors, the voltage wave-form is

improved.

(4) Static capacitors reduce the possibility of commutation failure. This is because of the large time constant, the voltage sustained in capacitors during period immediately subsequent to fault or sudden load change conditions in the a.c. systems, will not allow sudden voltage change, but it will allow the valves to adjust their firing angle with greater facility.

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

4.6. DEMERITS:-

(1) From figure 4.1(d), it is seen that the voltage across a valve (valve 4 in this case) is the sum of the voltages due to the transformer and the capacitor. There is no increase in peak value and thus there is no increase in voltage stress across the valve.

(2) The output voltage, which is also the sum of the voltages due to transformer and the capacitor, is shown by the dotted line in fig. 4.1(b). There is no change in either the mean value or the wave-shape of the output voltage. Thus the voltage harmonics on the d.c. side are similar to those arising in the case of natural commutation.

(3) The convertor is very much liable to be subjected to commutation failure when the value of I_d goes down. During commutation failure, the voltage across the capacitors may rise above the rated value. Though the protection against this can be provided by opening the by-pass valve and short-circuiting the direct-current side, but it is unlikely that

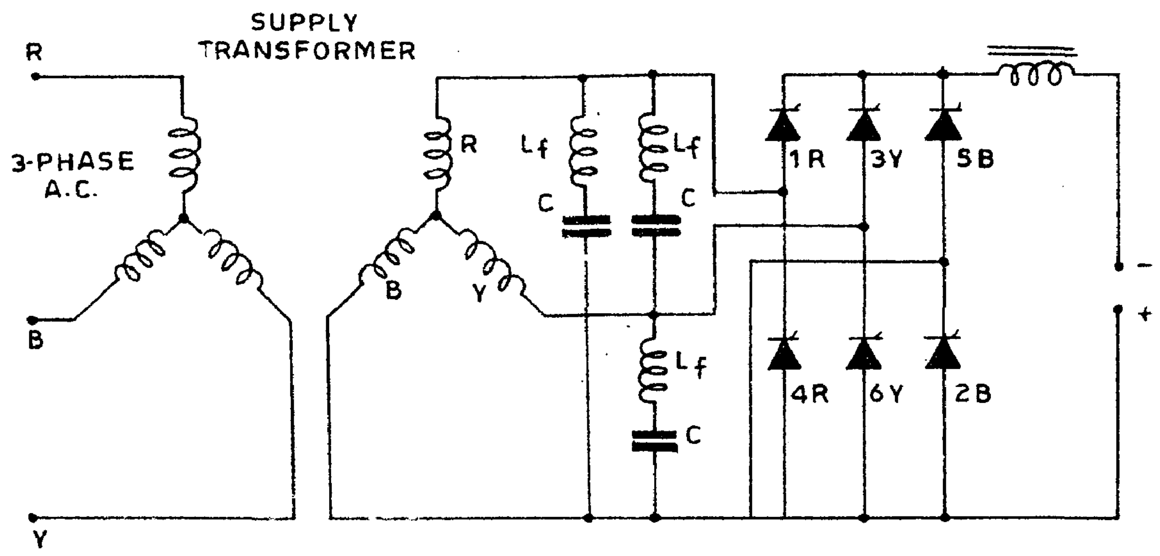


FIG.4.2-INVERTOR WITH SECONDARY CONNECTED FILTERS

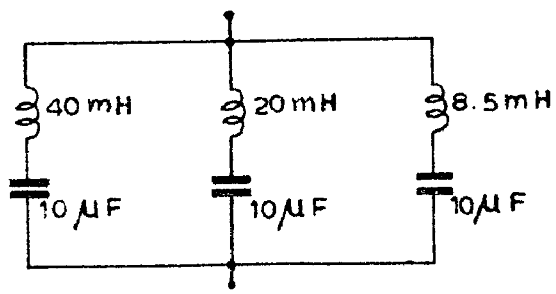


FIG. 4.3-FILTER BANK PER PHASE

the invertor would be able to resume the normal operation automatically as in the case of natural commutation.

(4) Starting may also present some difficulties.

Some of these above-mentioned difficulties in case of secondary-connected static capacitors, are removed in case of filter-circuits connected to the same side of the transformer.

4.7. SYNCHRONOUS CONDENSORS:

When the convertor rating is less than 1/5th of the system capacity, static capacitors are used, otherwise synchronous condensers are preferred. This is because synchronous condensors have better characteristics from regulation point of view.

The regulating arrangement, in the event when voltage falls due to load increase, will provide an increase in the KVAr, and prevent the system from running down. However, in this case the losses are more than in the case of static capacitors.

4.8. USE OF FILTER CIRCUITS FOR IMPROVING COMMUTATION ANGLE : (1,7,12)

The skematic diagram is shown in Fig.4.2. In this method, capacitors are replaced by filter circuits tunned to different frequencies. Filters are connected in shunt.

In this method, which remotes some of the difficulties discussed in case of secondary-connected static capacitors, a particular harmonic voltage at a suitable angle is superimposed on the fundamental voltage in such a way that it improves extra-commutation area where commutation takes place and delays the voltage zero at which the commutation and deionization should be complete. This enables the invertor to work at nearly unity power factor. The current contains some harmonics, and hence by providing filter circuits, the voltage of the required harmonics can be obtained superimposed upon the fundamental. The filters themselves must respond to the harmonics present in the alternating current wave-form.

With filter consisting of tunned circuits for a single frequency, a capacitor-recharge oscillation occurs at the end of commutation. Generally the tunned circuits for higher frequencies contribute more to the total short-circuit current owing to their higher rate of discharge current rise and by continuing the range of tunned circuits to cover further frequencies, commutation angle can be reduced to extremely low value.

With a filter of tunned circuits for fifth, seventh and eleventh harmonics as shown in Fig.4.3, a reduction in commutation angle of nearly 70% can be obtained.

It can be shown that in case of secondary - connected filter circuits in the fashion shown in Fig.(4.2), (Ref.7)

$$I_d = \frac{E}{\sqrt{2}\, WL}\left\{\mathrm{Cos}\,(\beta - \gamma^1) - \mathrm{Cos}\,\beta\right\} + \sum \frac{n^2}{n^2-1}\sqrt{2}\, E\, \mathrm{Sin}\,\beta.\ \frac{3}{2}\sqrt{\frac{C_\theta}{L_f}}\ \mathrm{Sin}\, n\gamma^1 \quad - (4.5)$$

where: $n = 5, 7, 11, 13$ etc. = The order of harmonics

$= K\,P \pm 1.$, where p is phase no. and K is any integer. For a 3-phase bridge connection, $p = 6$.

C, L_f are appropriate to the tunned circuit for each individual frequency.

γ^1 = Resultant commutation angle in degrees.

Without filter circuits:

$$I_d = \frac{E}{\sqrt{2}\, WL} \left\{ \cos \{(\beta - \gamma) - \cos \beta \} \right. \quad - \quad (4.4) \quad (\text{Ref.}1)$$

where γ = commutation angle for natural commutation.

<u>EXAMPLE</u>: - To illustrate the above method for improving commutation angle,

Let $L = 0.066$ p.u.

$V_o = 1$ p.u. , $\therefore E = \frac{\pi}{3\sqrt{2}} V_o = 0.74$ p.u.

$I_d = 0, \; 0.25 , \; 0.5 , \; 0.75 , \; 1.0$ p.u.

$C = 10\ \mu F$.

L_f = 40 mH, for fifth harmonic.

= 20 mH for seventh harmonic.

= 8.5 mH for eleventh harmonic.

Here, calculations are made to find out commutation angle for different values of currents at first for each tunned circuit separately and then for all the three filter circuits connected together from eqn. (4.5). These calculations are made by trial.

The same calculations are made for natural commutation from the equation (4.4).

All calculations are presented here in tabular forms:

(i) When filter circuit tunned to the fifth harmonic alone is connected: Then $C = 10\ \mu F$, $L_f = 40$ mH. $n = 5$. Calculations shown in Table 4.3:

I_d	0	0.25	0.5	0.75	1.0
γ (for natural commutation) in degrees	0	7.5	12.7	16.8	20.7
γ' (when tunned ckt used) in degrees	0	5.1	8.95	12.2	15.15
Improvement in angle $= \gamma - \gamma'$	0	2.4	3.75	4.6	5.55

Table 4.3

(ii) For filter ckt tunned to 7th harmonics:

$C = 10\ \mu F$, $L_f = 20$ mH, $n = 7$ - Calculations in Table 4.4:

I_d	0	0.25	0.5	0.75	1.0
γ	0	7.5	12.7	16-8	20.7
γ'	0	4.04	7.24	10.3	13.9
$\gamma - \gamma'$	0	3.46	5.46	6.5	6.8

Table 4.4.

(iii) For filter ckt tunned to 11th harmonic;

$C = 10\ \mu F, \quad L_f = 8.5$ mH

I_d p.u	0	0.25	0.5	0.75	1.0
γ	0	7.5	12.7	16.8	20.7
γ'	0	2.49	4.75	7.35	10.9
$\gamma - \gamma'$	0	5.01	7.95	9.45	9.8

Table 4.5

Thus we see that the improvement in commutation angle in case of filter circuits tunned to higher harmonic, is more than in the case of filter ckt tunned to lower harmonic as stated earlier.

(iv) When the three ckts are connected symultaneously, then the results obtained are shown in the Table 4.6:

I_d	0	0.25	0.5	0.75	1.0
γ	0	7.5	12.7	16.8	20.7
γ'	0	1.2	2.25	3.3	4.5
$\gamma - \gamma'$	0	6.3	8.45	15.5	16.2

Table 4.6

Thus we see that the maximum saving results, when all the three filter ckts tuned to 5th, 7th and 11th harmonics respectively, are connected simultaneously.

However, by adding the improvements in commutation angle from Tables (4.3), (4.4) and (4.5) & then comparing with Table (4.6), it can be seen that the saving in commutation angle due to all the three filter circuits connected together, is less than the sum of the savings obtained by connecting each filter circuit separately. This is because with filter consisting of tuned circuits for a single harmonic, a capacitor-recharge oscillation occurs at the end of the commutation.

Thus due to filters consisting of tuned circuits for different harmonics, appreciable saving in commutation angle can be achieved.

4.9. REACTIVE POWER CONSUMPTION AND ESTIMATED SAVING:

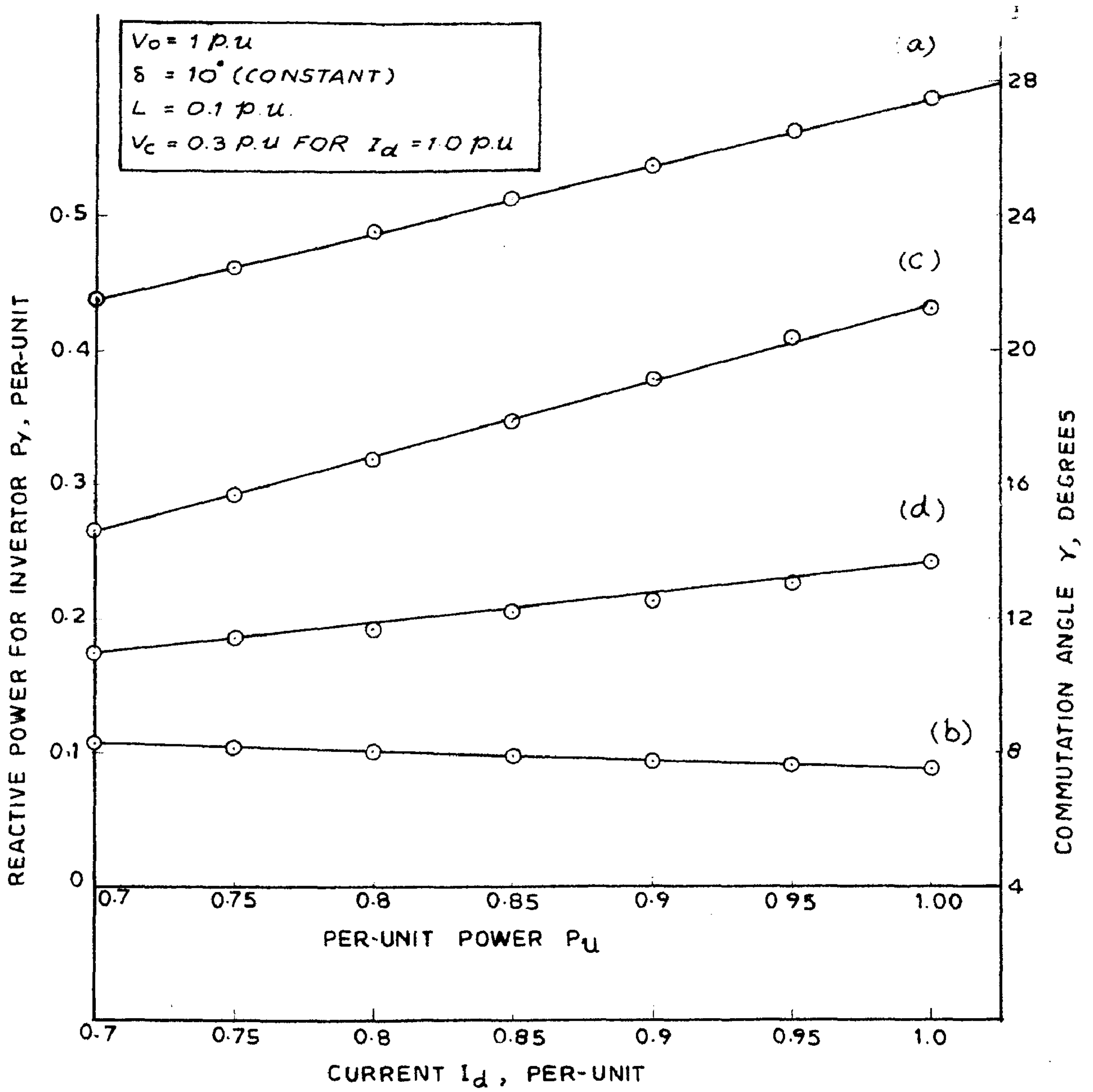
So far different methods have been discussed to improve the commutation angle that is how to reduce the reactive power demand required by the invertor for stable operation. Following paragraphs will show how reactive power depends upon under different methods.

It can be shown (Ref.7) that a.c. apparent, active and reactive powers under normal operating conditions are given by:

$$P_1 = \sqrt{3}\ EI = V_o I_d. \qquad (4.6)$$

$$P_1(a) = V_o I_d \ \frac{\cos\beta + \cos\delta}{2} \qquad (4.7)$$

$$P_1(r) = V_o I_d \ \frac{2\gamma + \sin 2\delta - \sin 2\beta}{4\ (\cos\delta - \cos\beta)} \qquad (4.8)$$



CURVE (a) - ν VS I_d WITHOUT CAPACITORS

CURVE (b) - ν VS I_d WITH CAPACITORS

CURVE (C) - P_Y VS P_u WITHOUT CAPACTTORS

CURVE (d) - P_Y VS P_u WITH CAPACITORS

ALL VALUES ARE IN PER UNITS

FIG. 4.4 - EFFECT OF SECONDARY CONNECTED STATIC CAPACITORS ON COMMUTATION ANGLE AND INVERTOR REACTIVE POWER CONSUMPTION

Equation (4.8) gives the value of reactive power demand for known values of γ . Here δ will be assumed to be constant at $\delta_o = 10^o$ throughout.

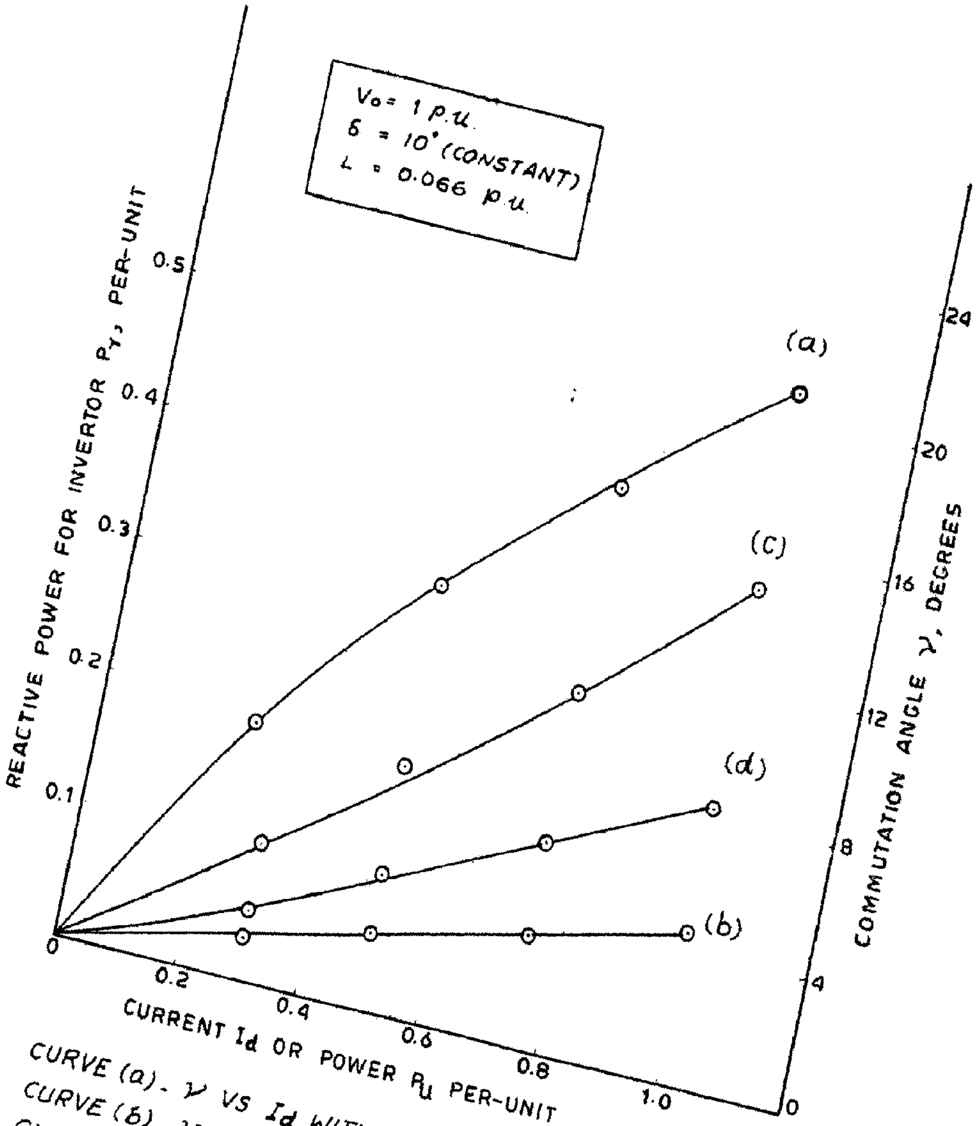
Case 1 :- When capacitors are used for improving the commutation angle, the reactive power consumption calculated from eqn. (4.8) for $V_o = 1.0$ p.u. and $\delta = \delta_o = 10^o$, is shown in Table 4.7:

I_d	1.00	0.95	0.9	0.85	0.8	0.75	0.7
γ (without capacitors)	27.5	26.5	25.5	24.55	23.6	22.5	21.5
γ' (with capacitors)	7.56	7.66	7.76	7.88	8.00	8.16	8.38

Table 4.7

Pu(p.u)	1.00	0.95	0.9	0.85	0.8	0.75	0.7
Pr(p.u) without capacitors	0.43	0.409	0.378	.349	.3183	.293	.266
Pr(p.u) with capacitors.	.242	.226	.2147	.206	.1904	.185	.175

Case 2 :- When filters consisting of tuned circuits are connected to the transformer secondaries for improving commutation angle; the reactive power demand calculated from equation (4.8) for $V_o = 1.00$ p.u., $\delta = \delta_o = 10^o$, is shown in Table (4.8):



CURVE (a) - ν VS I_d WITHOUT FILTER CIRCUITS
CURVE (b) - ν VS I_d WITH FILTER CIRCUITS
CURVE (c) - P_r VS P_u WITHOUT FILTER CIRCUITS
CURVE (d) - P_r VS P_u WITH FILTER CIRCUITS

5. EFFECT OF SECONDARY CONNECTED FILTER BANK ON COMMUTATION ANGLE AND INVERTOR REACTIVE POWER CONSUMPTION

I_d (p.u)	0	0.25	0.5	0.75	1.0
γ (without filters)	0	7.5	12.7	16.8	20.7
γ' (with filters)	0	1.2	2.25	3.3	4.5

Table 4.8

Using these values of γ & γ', Pr is calculated from the equation (c) for both the cases. The results obtained are as follows:

P_u (p.u)	0	0.25	0.5	0.75	1.0
P_r (p.u) without filters	0	0.101	0.182	0.268	.371
P_r (p.u) with filters	0	0.051	0.102	0.152	0.206

Relationships:- Figures 4.4 and 4.5 show the nature of variation of commutation angle for safe commutation and reactive power demand of an invertor with direct current. Curves (a) and (b) in figure 4.4 shows the nature of commutation angle with respect to direct current for natural commutation and for the case when capacitors are used respectively. Curves (c) and (d) have been plotted between A.C. power and reactive power demand for the same cases. Curves (a), (b), (c) and (d) in figure (4.5) indicate the aboverelationships respectively for the case when filter circuits have been used in place of static capacitors.

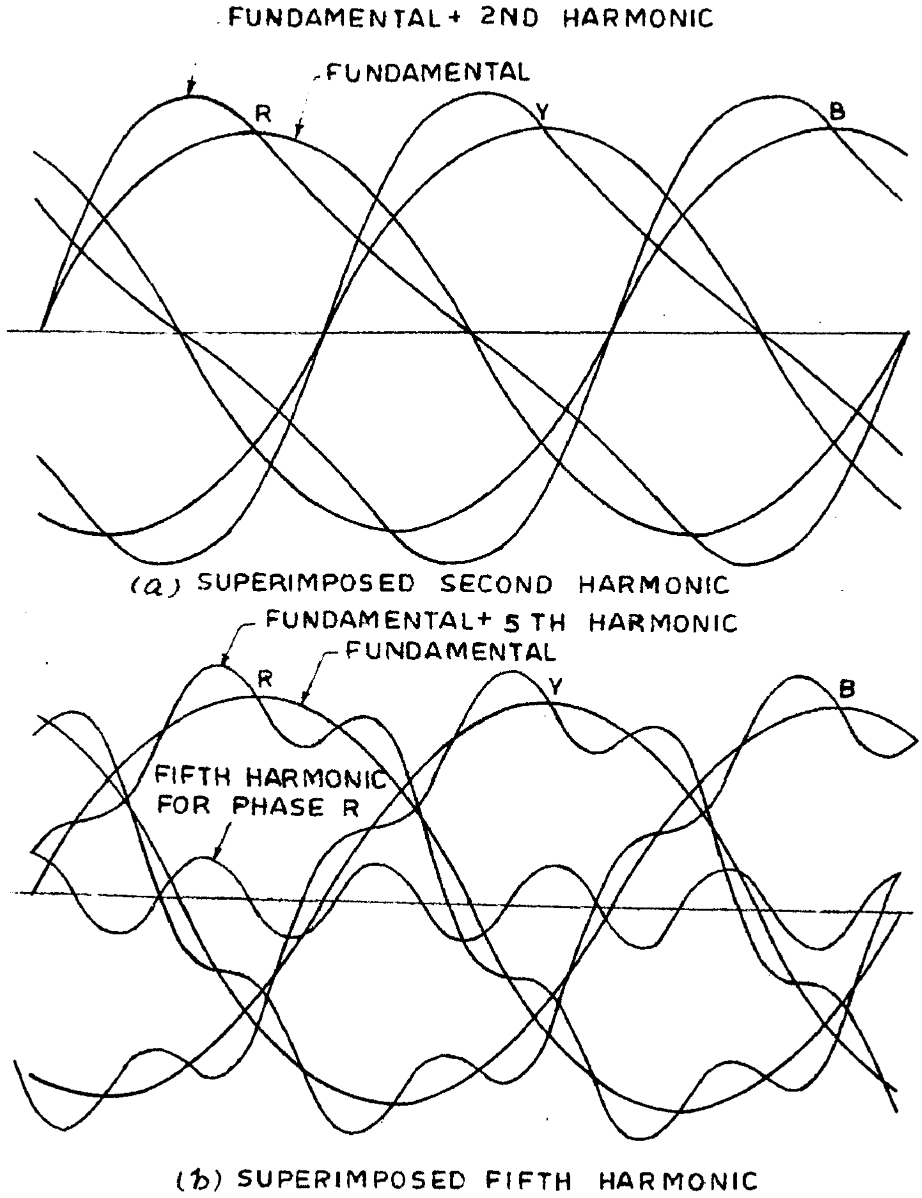


FIG. 4·6 INVERTOR WITH RESONANT COMMUTATION

4.10. CONCLUSIONS:

(1) Appreciable improvement in commutation angle and saving in reactive power demand is obtained by connecting static capacitors or filter circuits to the transformer secondary windings.

(2) Comparing the results obtained in case of filters and static capacitors, we see that the improvement in commutation angle and consequently saving in reactive power demand is more in case of filters than in the case of static capacitors.

(3) From figure 4.6, it is seen that the peak value of voltage, in case of tuned circuits, is increased because of the superimposed harmonics. Therefore the voltage stress on the valve will be increased, thereby reducing the rating of the valve. Fig. 4.1(d) indicates that there is no such advantage in case of bank of static capacitors.

(4) In case of tuned circuits, the convertor can operate stably for all values of currents, whereas in case of static capacitors convertor is very much liable to be subjected to commutation failure.

Automatic tuning arrangements for the filter circuits are to be provided to allow for variation in the supply frequency. No doubt the cost of the filter circuits and automatic tuning arrangements will be quite comparable to the cost of the capacitors, but seeing above mentioned advantages, it is expected that filters consisting of tuned circuits will replac static capacitors not in too distant future.

CHAPTER - 5 (Ref. 1,9,10)

" A method of analysing transient behaviour in circuits containing rectifiers, inductances and E.M.F's "

5.1. In analysing transient phenomenon in case of invertor, which is a device with discretely and periodicall varying parameters, the method of "difference equations" has been applied. The cases when the time intervals are constant in length with different parameters and also when the length of time intervals varies according to the nature ofthe transient phenomenon, have been discussed. The method developed for different cases of transients, has been demonstrated with suitable examples.

The method has been developed for 6 - Ø convertor.

Fig. 5.1.: e_1, e_2 and e_3 are three phase symmetrical e.m.fs. Xy is the inductive reactance upon which the commutation angle mainly depends. X is the inductive reactance of a reactor inserted in the line. This X limits the current rise through the invertor. It is required to determine the nature of the current i for different cases. To extend the method to wider range of problems, it is also assumed that the angle of advance β of the valves varies under the influence of grid control device.

The transient process starts at the instant θ_0. The valve which comes into operation at the instant θ_0 has got an angle of advance β_0 and it is β_1 for the next valve and so on.

One interval between the transients θn and θ_n+1 is considered. At the instant θn the valve 2 of the phase B and at θ_n+1 the valve 4 of the phase A start

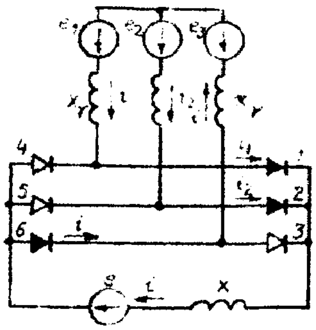


FIG. 5.1- SIX PHASE BRIDGE INVERTOR

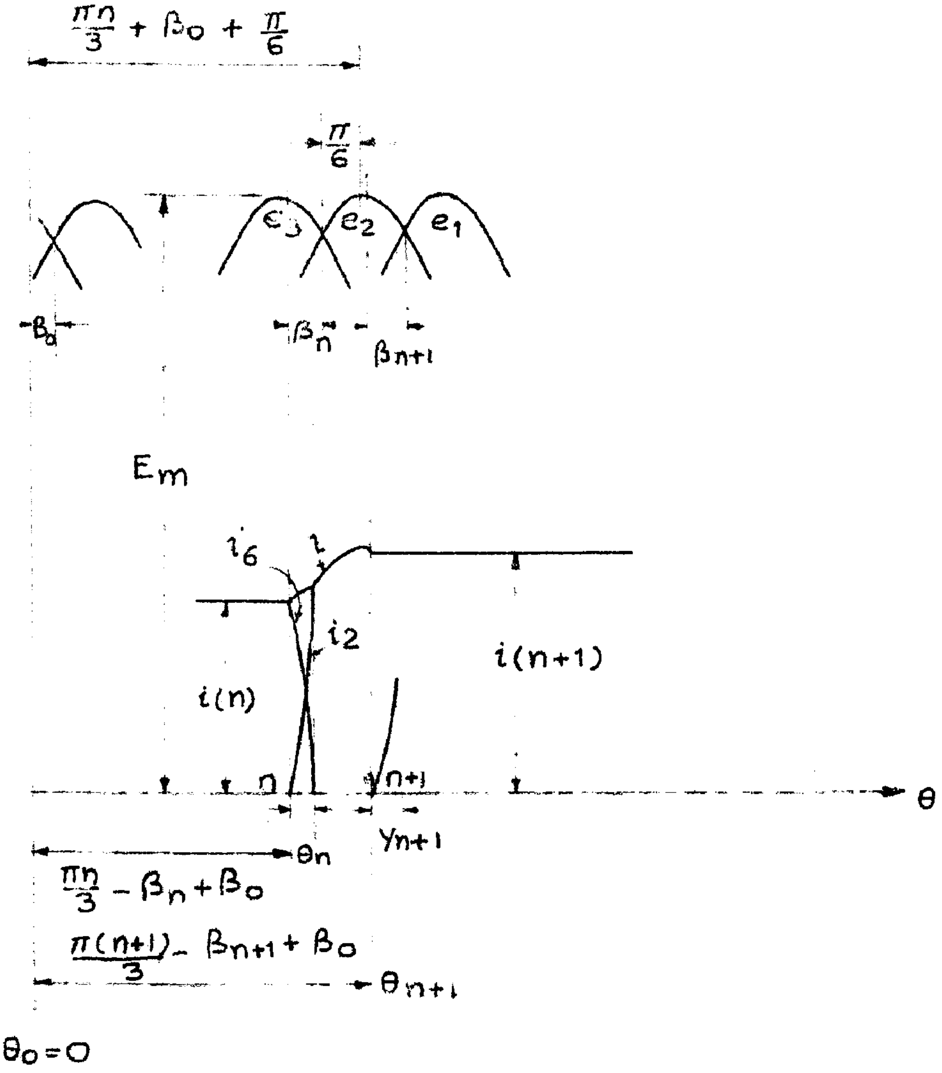


FIG 5.2- CURVES FOR e.m.f's AND CURRENTS IN ANALYSING TRANSIENT BEHAVIOUR IN THE CIRCUIT SHOWN IN FIG 5.1

firing with the angles of advance β_n and β_{n+1}, respectively. The whole transient process is divided into such intervals between the firing of one valve to the firing of the next. This overall interval is again divided into sub-intervals which are the commutation period γ_n and the "extra commutation" period. During the commutation period both the valwes 6 and 2 are conducting and during the extra-commutation period, only valve 2 is conducting.

5.2. DEVIATION OF DIFFERENCE EQUATIONS:

Assumptions:-

(i) Forward voltage drop in the valve does not depend upon the magnitude of the currents, therefore

$$V_{fwd} = \text{constant.}$$

(ii)The inverse current of the valve is zero.

(iii)In the transient process,

$$\gamma_n \leqslant \theta_{n+1} - \theta_n$$

(iv)The transient process starts with the firing of a valve at $\gamma_n = o$.

(v)The current i_2 throughout the overall interval $\theta_n - \theta_{n+1}$ is greater than zero.

(vi)Equation(5) below, holds also for overall intervals for which $\gamma_n = o$. Of course, this interval comes first on connecting the convertor.

Fig. 5.2. The valve 2 fires at the start of the overall interval $\theta_{n+1} - \theta_n$. By passing along through the circuit of the current i and through valve 2, the initial equations

are represented as :

$$(X + Xy)\ \frac{di}{d\theta} + Xy\ \frac{di_2}{d\theta} = f\ (\theta) \qquad \ldots\ldots\ldots\ldots \qquad (1)$$

$$\text{where}\ f\ (\theta) = e_2 - e - 2\ V_{fwd.} \qquad \ldots\ldots\ldots\ldots \qquad (2)$$

The eqn. (1) holds good both for the commutation subinterval as well as extra-commutation subinterval. For the commutation interval $i = i_2 + i_6$ and for the extra-commutation interval $i = i_2$. Therefore it is justified to integrate the eqn. (1) throughout the overall interval i.e. between θ_n and θ_n+1.

After integration:

$$(X + Xy)\ \left| i \right|_{\theta_n}^{\theta_n+1} + Xy\ \left| i_2 \right|_{\theta_n}^{\theta_n+1} = \int_{\theta_n}^{\theta_n+1} f(\theta)\ d\theta. \qquad (3)$$

Let, $i\ (\theta_n) = i(n)$ and $i(\theta_{n+1}) = i\ (n+1)$

Also, $i_2(\theta_n) = o$ and $i_2\ (\theta_{n+1}) = i\ (\theta_n+1) = i\ (n+1)$ (4)

After substituting (4) in (3), we get,

$$(X + Xy + Xy)\ i\ (n+1) - (X + Xy)\ i(n) = \int_{\theta_n}^{\theta_n+1} f\ (\theta)\ d\theta.$$

Let, $X + X_r = a$ and $X_r = b$

Then from above,

$$(a+b)\ i\ (n+1) - a\ i\ (n) = \int_{\theta_n}^{\theta_n+1} f(\theta)\ d\theta \qquad \ldots\ldots\ldots \qquad (5)$$

$n = 0,1,2,3,\ldots$ etc. and represents the successive instants of firing of the valves. It is assumed for the sake of simplicity that the transient process starts with the firing of a valve at $n = o$. Then from the start of the transient process, θ_n & θ_n+1 are given by angular units as below:

$$\left.\begin{aligned} \theta_n &= \frac{2\pi n}{6} - \beta_n + \beta_o \\ &= \frac{\pi n}{3} - \beta_n + \beta_o \\ \& \quad \theta_{n+1} &= \frac{2\pi n}{6} - \beta_{n+1} + \beta_o \\ &= \frac{\pi n}{3} - \beta_{n+1} + \beta_o \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (6)$$

Now in eqn. (2) the e.m.f. e will be constant or variable in time. But V_{fwd} and e in the function $f(\theta)$ will be the same in any overall interval. This system of the phase e.m.f's is symmetrical. The general expression for $f(\theta)$ which holds for only overall interval with bounds given by the expression (6) is thus:

$$f(\theta) = \sqrt{3} \ Em \ Cos \ (\theta - \frac{\pi n}{3} - \beta_o - \frac{\pi}{6}) - e - 2 V_{fwd} - ($$

Thus, the eqn.(5), taken along with expressions (6) and (7), is the different equation for the transient conditions for a 6-phase invertor.

Substituting the value of $f(\theta)$ from the eqn.(7) in eqn.(5), we obtain,

$$(a+b)i \ (n+1) - a^{i}(n) = \sqrt{3}\,i\,Em \left| Sin(\theta - \frac{\pi n}{3} - \beta_o - \frac{\pi}{6}) \right|_{\theta n}^{\theta n+1}$$

$$- 2 \ V_{fwd} \Big|_{\theta_n}^{\theta_{n+1}} - \int_{\theta n}^{\theta n+1} e d\theta$$

After substituting the values of θ_n and θ_{n+1} from expression(6),

$(a+b) \ i \ (n+1) - a \ i \ (n)$

$$= \sqrt{3} \ Em \left[Sin \ (\frac{\pi n}{3} + \frac{\pi}{3} - B_{n+1} + \beta_o - \frac{\pi n}{3} - \beta_o - \frac{\pi}{6} \ ) \right.$$

$$\left. - \ sin \ (\frac{\pi n}{3} - \beta_n + \beta_o - \frac{\pi n}{3} - \beta_o - \frac{\pi}{6}) \right]$$

$$- 2 V_{fwd} \left(\frac{2\pi}{6} - \beta_{n+1} + \beta_n \right) - \int_{\theta_n}^{\theta_{n+1}} e d\theta$$

$$= \sqrt{3} \quad Em \left[Sin \left(\frac{\pi}{6} - \beta_{n+1} \right) - Sin \left(-\beta_n - \frac{\pi}{6} \right) \right] + \text{" "} + \text{" "}$$

$$= \sqrt{3} \quad Em \left[Sin \left(\beta_n + \frac{\pi}{6} \right) + Sin \left(\frac{\pi}{6} - \beta_{n+1} \right) \right] + \text{" "} + \text{" "}$$

$$= \sqrt{3} \quad Em \left[2 \, Sin \left(\frac{\pi}{6} + \frac{\beta_n - \beta_{n+1}}{2} \right) cos \frac{\beta_n + \beta_{n+1}}{2} \right] + \text{"} +$$

$$= 2\sqrt{3} \quad Em \quad Sin \left(\frac{\pi}{6} + \frac{\beta_n - \beta_{n+1}}{2} \right) cos \frac{\beta_n + \beta_{n+1}}{2}$$

$$- 2 V_{fwd} \left(\frac{\pi}{3} - \beta_{n+1} + \beta_n \right) - \int_{\theta_n}^{\theta_{n+1}} e \, d\theta \quad \ldots\ldots\ldots (8)$$

5.3. ANALYSIS OF DIFFERENT TYPES OF TRANSIENTS:

The analysis of transient behaviour for different cases is discussed below:

Case I:- The convertor operates as an invertor and on the d.c. side, there is a constant e.m.f.

$$e = -Vd = \text{const.}$$

The angle of advance for each valve being the same.

Thus, $\beta_n = \beta_{n+1} = \beta = \text{const.}$

$$e = - Vd.$$

Substituting these valves and eqn. (6) in eqn.(8) we get,

$$(a+b) \; i\,(n+1) - a \; i\,(n)$$

$$= 2\sqrt{3} \quad Em \; Sin \frac{\pi}{6} Cos \; \beta - 2 V_{fwd} \frac{\pi}{3} + Vd \frac{\pi}{3}$$

$$= \frac{\pi}{3} \left[\sqrt{3} \quad Em \; \frac{3}{\pi} \cdot Cos \; \beta - 2 V_{fwd} + Vd) \right]$$

$$= \frac{\pi}{3} \left[\frac{3\sqrt{3}}{\pi} Em \quad Cos \; \beta - 2 V_{fwd} + Vd \right] - \qquad (9)$$

Since Vd and β are constant, therefore, eqn. (9) which describes the transient behaviour in this case, is a first order linear difference equation with a constant right hand side. The solution is, therefore, found in the form $i(n) = i(n)' + i(n)''$ when $i(n)'$ is a partial solution and $i(n)''$ is the general solution of the homogeneous equation.

To find out the partial solution, in eqn.(9) we put the condition

$$i(n+1) = i(n) = i(n)'$$

Thus,

$$i(n)' = \frac{\frac{3\sqrt{3}}{Em} \cos\beta - 2V_{fwd} + Vd}{\frac{3}{\pi} X_{\gamma}}$$

Now, let $i(n)'' = C\lambda''$. Then the general solution of the homogeneous difference equation obtained from (9) is

$$\lambda = \frac{a}{a+b}$$

Thus,

$$i(n) = i(n)' + C\lambda^{n}.$$

To find out the constant C, it is assumed that at the start of the transient process (i.e. at n=o),

$i(n) = i(o)$.

Then $C = i(o) - i(n)'$

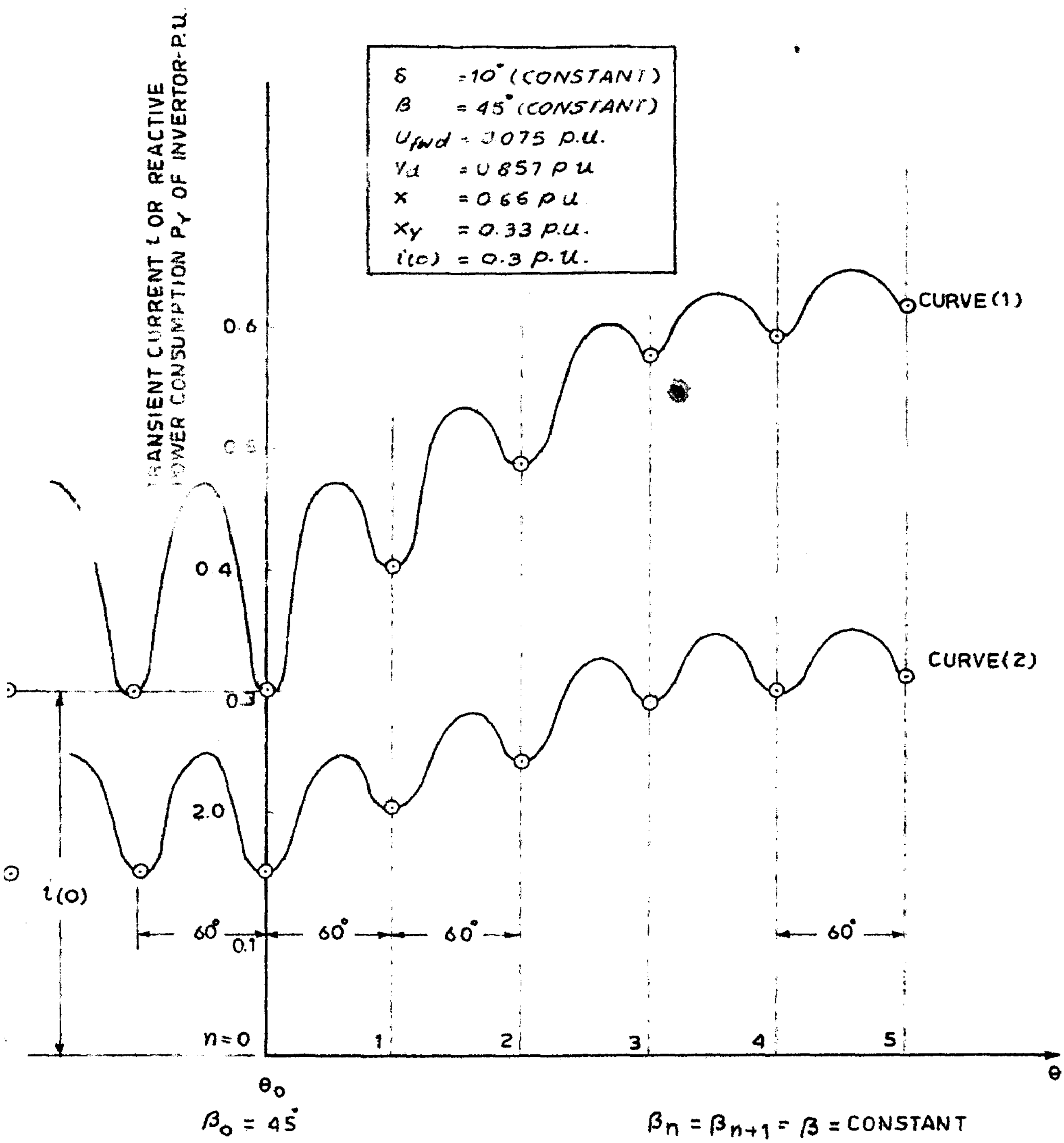
So,

$$i(n) = i(n)' + \left[i(o) - i(n)'\right]\left\{\frac{a}{a+b}\right\}^{n}$$

Substituting for a and b in above, finally we get,

$$i(n) = i(n)' + \left[i(o) - i(n)'\right]\left\{\frac{X + X_{\gamma}}{X + 2X_{\gamma}}\right\}^{n} \quad \ldots\ldots \quad (12)$$

From eqn. (12), discrete values of the current i(n) in the transient process can be calculated.



G.5.4-VARIATION OF TRANSIENT CURRENT AND REACTIVE POWER DEMAND OF INVERTOR ($e = V_d$ = CONSTANT, β = CONSTANT)

Such type of transient process is caused by a step type change at the start of the transient process in the following quantities which affect $i(n)'$, Vd, Em, β and X_γ.

EXAMPLE:-

Let $V_o = 1$ p.u. $\quad$ S.E $= \frac{\pi}{3\sqrt{2}} V_o = 0.74$ p.u.

$Em = \sqrt{2}E = \sqrt{2} \times 0.74 = 1.047$ p.u.

Taking the voltage drop due to valves into account,

$Vd = V_o \cos\beta + 2 V_{fwd}$

Let $\beta_n = \beta_{n+1} = \beta = 45^o$ (say)

$V_{fwd} = 0.075$ p.u.

$Vd = 0.857$ p.u.

Let $X = 2 X_\gamma$

$X = 0.66$ p.u (say), So, $X_\gamma = 0.33$ p.u.

Let at the start of the transient process i.e. at $n = 0$, $i(n) = i(o) = 0.3$ p.u.

From above at first $i(n)'$ is found out, and then the eqn.(12) enables to calculate for $i(n)$. The expression for the reactive power is $Pr = V_o Id \dfrac{2\gamma + \sin 2\delta - \sin 2\beta}{4\,(\cos\delta - \cos\beta)}$ under steady state. Assuming $\delta = \delta_o = 10^o$ = const. the above eqn. enables us to find out the value of reactive power required for the points n = 0, 1,2,3 etc. only. The results are tabulated as below:

$\delta = \delta_o = 10^o$, $\beta = 45^o$, $\gamma = 35^o$, $V_o = 1.00$ p.u.

n	0	1	2	3	4	5
i(n) p.u.	0.3	0.403	0.482	0.575	0.593	0.6162
Pr(p.u)	0.1515	0.2038	0.2435	0.29	0.300	0.3115

The nature of variation of i(n) and Pr with respect to n has been shown in Fig.5.4 by curves (a) and (b) respectively.

Case 2 :-

The convertor is operating as an invertor and on the d.c. side, there is a constant e.m.f.

$$e = - Vd = \text{const.}$$

But the angle of advance of the values is changing during the transient process.

Such case occurs when the firing angle of the valves can vary under the influence of grid control devices, such that the current i is a function of the angle of firing of the valves.

Let the invertor is operating in steady state with some angle β_o and the transient process starts at n=o. To obtain the relationship in closed form a linear relationship between the angle β_n and n is assumed. Let in course of p intervals there be a gradual linear increase in the angle β_n as:

$$\left.\begin{aligned} \beta_n &= \beta_o + \left(\ell \cdot \frac{2\pi}{6}\right) n. \\ &= \beta_o + \ell \frac{\pi}{3} n \quad \text{if} \quad o \leq n \leq p. \\ \beta_{n+1} &= \beta_o + \ell \frac{\pi}{3} (n+1) \\ \beta_n &= \beta_p = \beta_o + \left(\frac{\ell\pi}{3}\right) p \quad \text{if} \quad n \geq p \end{aligned}\right\} \ldots (13)$$

After substituting for θ_n and θ_{n+1} from (6) and β_n, β_{n+1} from (13), eqn. (8) under above conditions results in:

$$(a+b)\, i(n+1) - a\, i(n)$$

$$= 2\sqrt{3}\, Em \; Sin\left[\frac{\pi}{6} + \frac{\ell\frac{\pi}{3}n - \ell\frac{\pi}{3}(n+1)}{2}\right]$$

$$\times \; Cos \; \frac{2\beta_o + 2n\ell\frac{\pi}{3} + \ell\frac{\pi}{3}}{2} - 2V_{fwd}\left(\frac{\pi}{3} - \frac{\ell\pi}{3}\right) + Vd\left(\frac{\pi}{3} - \frac{\ell\pi}{3}\right)$$

$$= (1-\ell)\frac{\pi}{3}(Vd - 2V_{fwd})$$

$$+ 2\sqrt{3}\; Em\; Sin\left(\frac{\pi}{6} - \frac{\ell\pi}{6}\right) \times Cos\left(\beta_o + \ell n\frac{\pi}{3} + \frac{\ell\pi}{6}\right)$$

$$= (1-\ell)\frac{\pi}{3}.\;(Vd - 2V_{fwd}) + 2\sqrt{3}\; Em\; Sin\left\{(1-\ell)\frac{\pi}{6}\right\} Cos\left(\beta_o + \frac{\ell\pi}{6} + \frac{\ell\pi}{3}n\right) \quad .....(14)$$

Eqn.(14) is a 1st order linear difference eqn. One part of the right hand side is a constant quantity and the other part of it varies cosinusoidally with n.

The partial solution of (14) is found in the form

$$i(n) = A + L\; Cos\left(\beta_o + \frac{\ell\pi}{6} + \frac{\ell\pi}{3}n\right) + N\; Sin\left(\beta_o + \frac{\ell\pi}{6} + \frac{\ell\pi}{3}n\right).$$

The solution of this eqn. is

$$i(n) = i(n)' + i(n)''$$

$$= A + M\; Cos\left(\beta_o + \frac{\ell\pi}{6} - \psi + \ell\frac{\pi}{3}n\right) + C\lambda^n - (14$$

where
$$A = \frac{(1-\ell)\;(Vd - 2V_{fwd})}{\frac{3}{\pi}.b}$$

$$= \frac{(1-\ell)\;(Vd - 2\,V_{fwd})}{\frac{3}{\pi}\; X_\gamma}$$

$$M = \frac{2\sqrt{3}\;\; Em.\; Sin(1-\ell)\frac{\pi}{6}}{(a+b)\sqrt{1 + 2\sqrt{3}\lambda Cos\,\ell\frac{\pi}{3} + \lambda^2}}$$

$$= \frac{2\sqrt{3}\;\; Em\;\; Sin\;(1-\ell)\frac{\pi}{6}}{(X+2X\psi)\sqrt{1 + 2\sqrt{3}\;\lambda\; Cos\,\ell\frac{\pi}{3} + \lambda^2}}$$

$$\psi_\lambda = \arc \tan \frac{-\sin l\frac{\pi}{3}}{\lambda + \cos l\frac{\pi}{3}}$$

$$\lambda = \frac{a}{a+b} = \frac{X + X_\gamma}{X + 2X_\gamma}$$

at n=o, $i(n) = i(o)$.

Then from eqn. (14a)

$$C = i(o) - A - M \cos\left(\beta_o + l\frac{\pi}{6} - \psi\right)$$

Substituting for C in 14(a), we get,

$$i(n) = A + M \cos\left(\beta_o + l\frac{\pi}{6} - \psi + l\frac{\pi}{3}n\right) + i(o)\lambda^n.$$

$$-A\lambda^n - M \cos\left(\beta_o + l\frac{\pi}{6} - \psi\right)\lambda^n$$

$$= A(1-\lambda^n) + M\left[\cos\left(\beta_o + l\frac{\pi}{6} - \psi + l\frac{\pi}{3}n\right) - \cos\left(\beta_o + l\frac{\pi}{6} - \psi\right)\lambda^n\right] + i(o)\lambda^n \quad (15)$$

EXAMPLE:-

For illustrating the transient process, we take

$V_d = 0.85$ p.u. $V_{fwd} = 0.075$ p.u.

At n=o, $i(n) = i(o) = 0.1$ p.u.

$\beta_o = 45^o$, $X = 0.66$ p.u., $X_\gamma = 0.33$ p.u.

$\beta_n = \beta_o + l\frac{\pi}{3}n = \beta_o + 1.1\,n$ (say)

From above l, λ, ψ and then A & M are calculated. The current $i(n)$ is calculated from eqn.(15), after substituting the values of l, λ, ψ, A and M. for n = 0,1,2,3,4,5 between the interval $\theta_o - \theta_1$. Thereafter the angle β is constant during the transient process. Therefore the current i between $\theta_1 - \theta_2$ is calculated from eqn.(12). The reactive power required is calculated as previously for V_o=1.00 p.u. and $\delta = \delta_o = 15^o$. The results obtained are tabulated as:

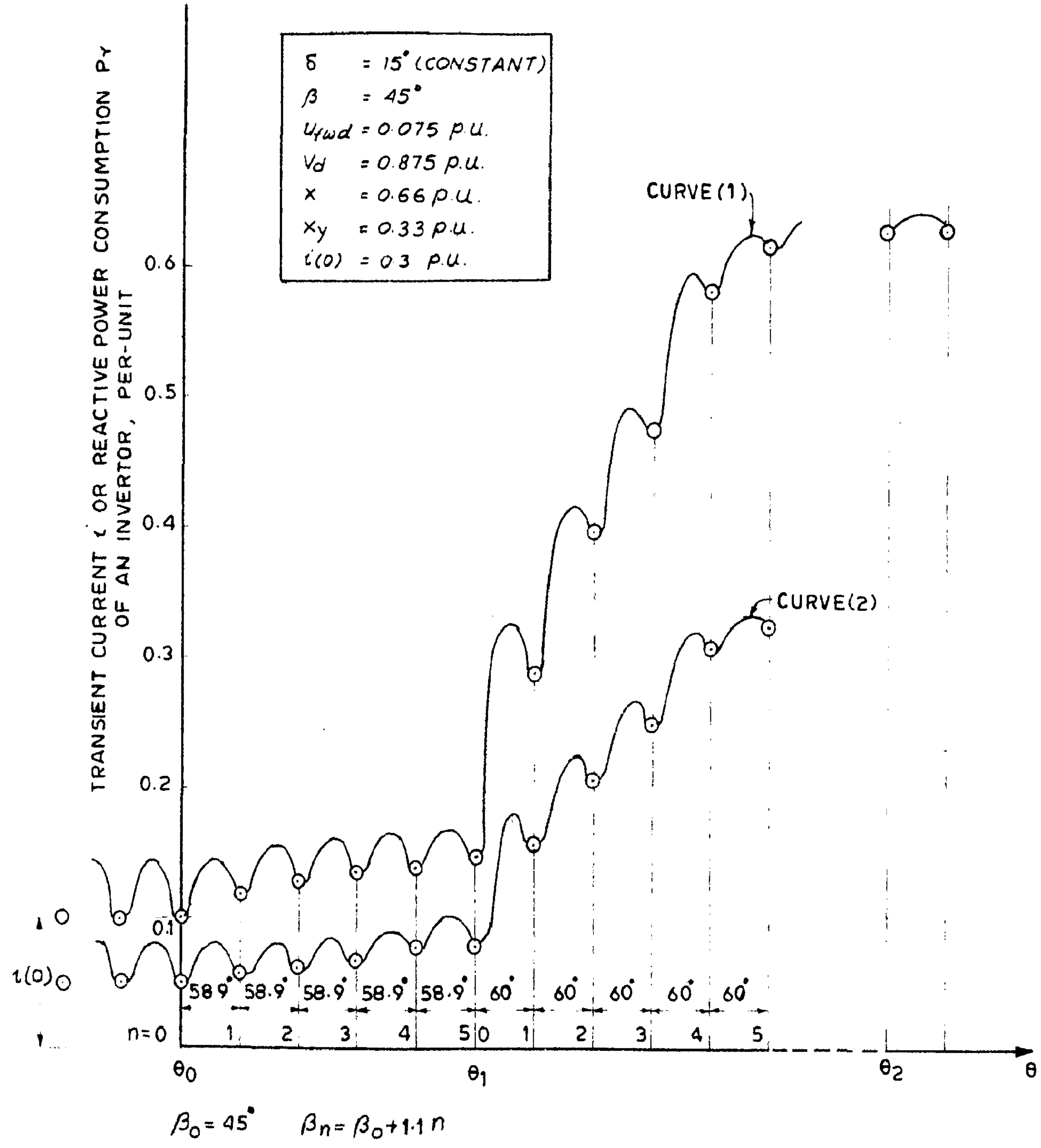


FIG. 5.5 - VARIATION OF TRANSIENT CURRENT AND REACTIVE POWER CONSUMPTION OF AN INVERTOR ($e = -V_d$ = CONSTANT, $\beta_n = \beta_0 + 1.1n$)

	$\theta_o-\theta_1$						$\theta_1-\theta_2$						
n	0	1	2	3	4	5	0	1	2	3	4	5	6
β	45	46.1	47.2	48.3	49.4	50.5	45	45	45	45	45	45	45
i (p.u)	0.1	0.1196	0.1305	0.1350	0.1395	0.1469	0.1469	0.289	0.396	0.4745	0.58	0.614	
Pr (p.u)	0.0528	0.058	0.0644	0.0682	0.0789	0.0845	0.0776	0.158	0.209	0.25	0.306	0.324	

Curves (a) and (b) in figure (5.5) present the nature of i(n) and Pr respectively.

Case 3 :-

The convertor operates as an invertor. The angle of advance of the valves remains constant throughout the transient behaviour, but the e.m.f. on d.c. side varies.

Let $e = - V_o$ during the steady state process. Then at some instant which coincide with the firing of one of the valves in succession, the voltage on the d.c. side begins to vary according to:

$$e = - Vd + (Vd - Vo)\, e^{-\frac{\theta_m m}{2\pi\tau}} \quad - \quad (16)$$

Here the time constant τ is measured in relative units (the duration $\frac{2\pi}{m}$ of the overall interval being taken as reference). The e.m.f. varies from $- V_o$ to Vd. The limits are such that the valves have got sufficient deionisation angle during the transient behaviour to avoid the commutation failure due to short circuit of any phase.

In this case, $\beta_n = \beta_{n+1} = \beta =$ const.

As before,

$$\theta_n = \frac{\pi n}{3} - \beta_n + \beta_o$$

$$\theta_{n+1} = \frac{\pi(n+1)}{3} - \beta_{n+1} + \beta_o$$

$$\int_{\theta n}^{\theta n+1} e\, d\theta = \int_{\theta_n}^{\theta n+1} \left[- Vd + (Vd - V_o) e^{-\frac{\theta m}{2\pi\tau}} \right] d\theta$$

$$= - \frac{\pi}{3} Vd - \frac{\pi\tau}{3} (Vd - V_o) \left[e^{-\frac{n+1}{\tau}} - e^{-\frac{n}{\tau}} \right]$$

$$\text{\_\_\_\_\_\_\_\_} \quad (16\text{-}a)$$

After substituting the eqn. (16-a) in eqn. (8), the difference equation reduces to:

$$(a+b)\, i(n+1) - a i(n)$$
$$= \sqrt{3}\ Em\ Cos\ \beta - \frac{2\pi}{3} V_{fwd} + \frac{\pi}{3} Vd + \frac{\pi}{3}\tau (Vd - V_o) \left\{ \bar{e}^{\frac{n+1}{\tau}} - \bar{e}^{\frac{n}{\tau}} \right\}$$

$$(a+b)\, i(n+1) - a\, i(n) = \frac{\pi}{3} \left[\frac{3\sqrt{3}}{\pi} Em\ Cos\ \beta - 2\, V_{fwd} + Vd \right] + \frac{\pi}{3} \tau (Vd - V_o) \left\{ \bar{e}^{\frac{n+1}{\tau}} - \bar{e}^{\frac{n}{\tau}} \right\} \quad -(17$$

The solution of the difference equation(17) found as before is:

$$i(n) = i(n)' + N\, \bar{e}^{\frac{n}{\tau}} + \left[i(o) - i(n)' - N \right] \left(\frac{a}{a+b} \right)^n$$
$$= i(n)' + N\, \bar{e}^{\frac{n}{\tau}} + \left[i(o) - i(n)' - N \right] \left\{ \frac{X + X_\gamma}{X + 2\, X_\gamma} \right\}^n$$

Where,

$$i(n)' = \frac{\frac{3\sqrt{3}}{\pi}\ Em\ Cos\ \beta - 2\, V_{fwd} + Vd}{\frac{3}{\pi} X\ b}$$
$$= \frac{\frac{3\sqrt{3}}{\pi} .\ Em\ Cos\ \beta - 2\, V_{fwd} + Vd}{\frac{3}{\pi} \cdot X_\gamma} \qquad (17-a)$$

and

$$N = \frac{\frac{\pi}{3} \tau (Vd - Vo)\ (1 - \bar{e}^{\frac{1}{\tau}})}{a - (a+b)\ e^{-\frac{1}{\tau}}}$$
$$= \frac{\frac{\pi}{3} \tau (V_d - Vo)\ (1 - e^{-\frac{1}{\tau}})}{(X + X_\gamma) - (X + 2\, X_\gamma)\ e^{-\frac{1}{\tau}}} \quad - \quad (17-b)$$

EXAMPLE: -

Let V_{fwd} = 0.075 p.u.
X = 0.66 p.u.
X_γ = 0.33 p.u.
Vo = 1.00 p.u.

Then,
Em = 1.047 p.u.

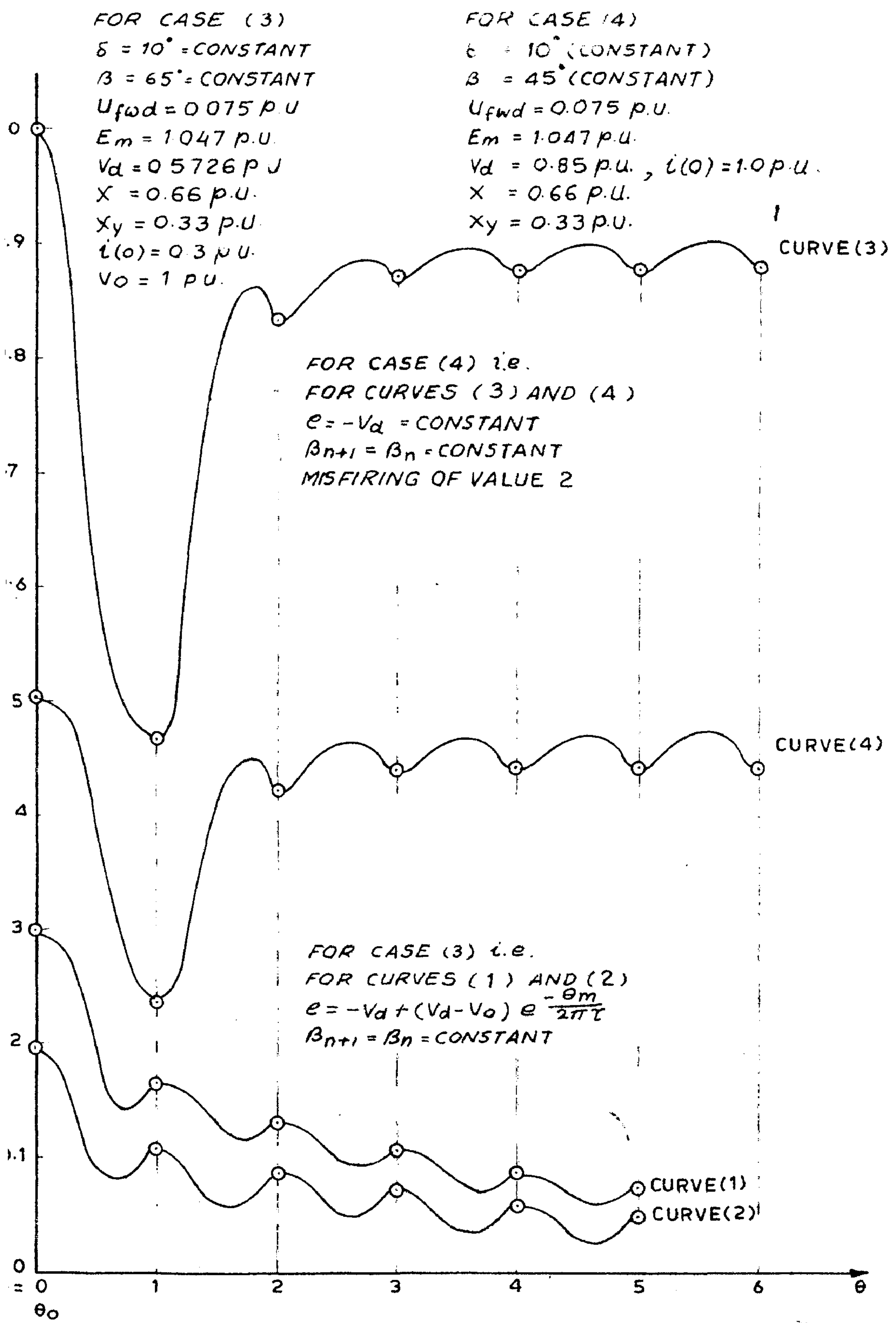


FIG.5.6-VARIATION OF TRANSIENT CURRENT AND REACTIVE POWER CONSUMPTION OF AN INVERTOR

The suitable values of the time constant τ and the angle of advance β are assumed to be 0.25 and 65° respectively.

$$Vd = V_0 \cos \beta + 2 V_{fwd} = 0.5726 \quad p.u.$$

$$At.\ n = o, \quad let \quad i(n) = i(o) = 0.3 \ p.u.$$

The values of i(n) and N calculated from (17-a) and (17-b) are found to be 0.033 and 0.091.

Substituting the above values in equation (17), the current i(n) for n = 1,2,3,4 and 5 is calculated.

The reactive power required for the operation of the invertor is calculated as before for V_0 = 1.00 p.u.

$$\delta = \delta_0 = 10°, \quad \beta = 65°.$$

The results obtained are put in the table :

n	0	1	2	3	4	5
i(n) p.u	0.3	0.165	0.132	0.1076	0.0886	0.075
Pr p.u.	0.1995	0.1098	0.0879	0.0716	0.059	0.0499

Curves (a) and (b) in figure (5.6) indicate the nature of variation of i(n) and P_r with respect to n

Case 4:-

Let the convertor is operating as an invertor with β = const. and e = - Vd. Then at a certain instant, there is misfire on one of the valves. In our case let it be valve 2, which ceases to fire. Due to this reason, a

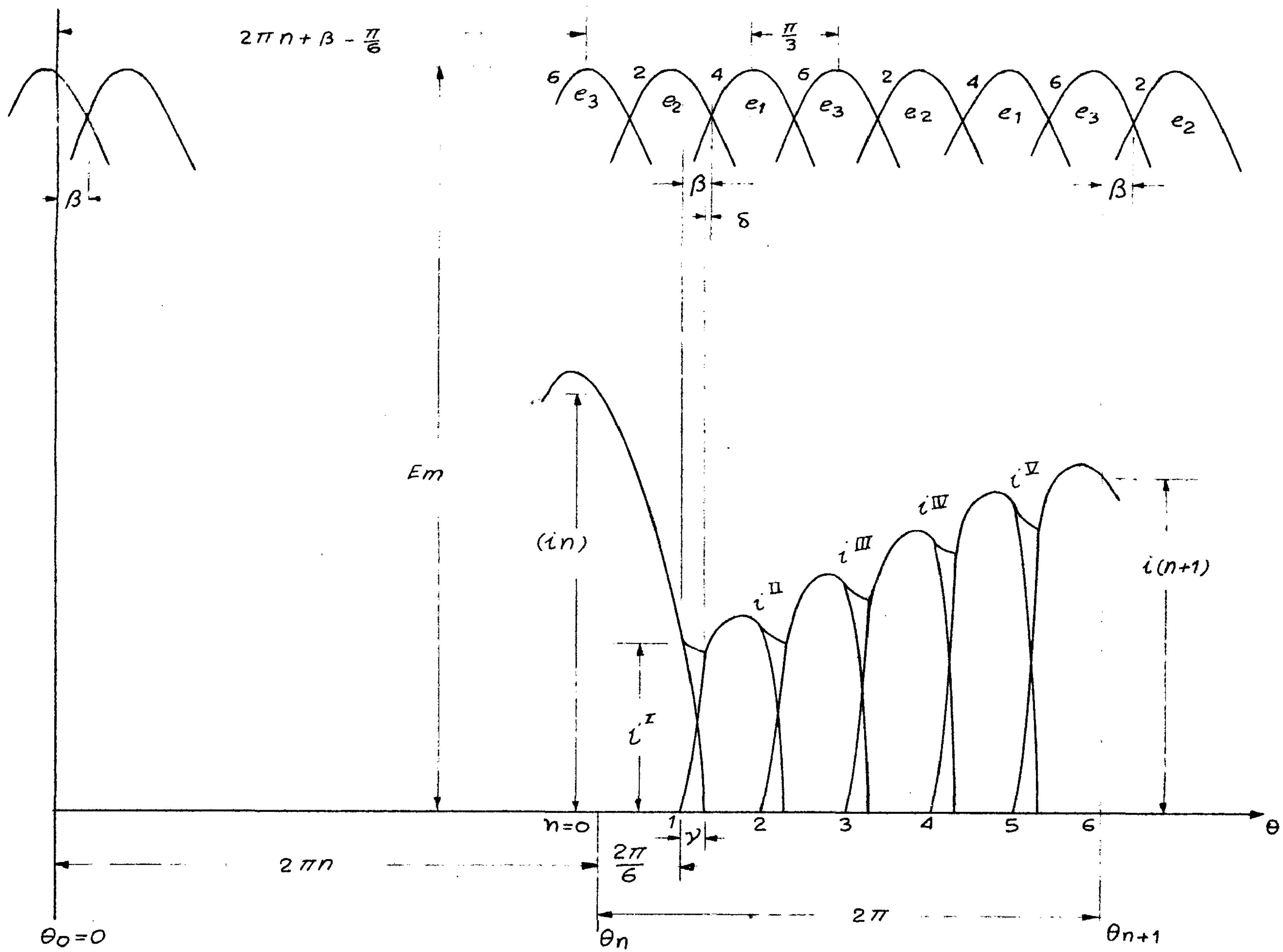


FIG. 5.3 - CURVES FOR e. m. f's AND CURRENT (IN ANALYSING TRANSIENT BEHAVIOUR UPON THE MISFIRING OF A VALUE

transient process starts. A new steady-state is settled with five valves, i.e. valves 1,3,4,5,6 in operation. The current i does not drop to zero because of the large inductance of the reactor when the valve 2 ceases to fire. In this case the overall interval, which is the interval between the firing of one valve and the firing of the next, consists of several intervals. Referring to the Fig. (5.3) the overall interval has got 6 sub-intervals which are 0-1, 1-2, 2-3, 3-4, 4-5 and 5-6 respectively. The interval 0-1 is the interval of misfire of the valve 2 to the firing of the valve 4, the sub-interval 1-2 is between the firing of the valve 4 and the firing of the valve 6. The bounds of any overall interval from 1st misfire are:

$$\theta_n = 2\pi n \quad \text{and} \quad \theta_{n+1} = 2\pi(n+1).$$

Let the current i at the bounds 0,1,2,3,4,5 and 6 are $i(n)$, i^{I}, i^{II}, i^{III}, i^{IV}, i^{V} and $i(n+1)$. Let us find out the difference equation relating $i(n)$ and $i(n+1)$.

Since the valve 2 does not fire at the instant, therefore between 0-1, the valve 6 is 'ON'. From Figs. 1 & 3 for the interval 0-1, we have :

$$(a+b)\frac{di}{d\theta} = e_3 + E - 2V_{fwd}$$

$$= \sqrt{3}\ Em \cos\left(\theta - 2\pi n - \beta + \frac{\pi}{6}\right) + Vd - 2V_{fwd}$$

The limits of integration for above are:

$$\theta_n = 2\pi n\ , \ \& \ \theta_1 = 2\pi n + \frac{2\pi}{m} = 2\pi n + \frac{\pi}{3}$$

After integrating the above:

$$(a+b)\,i' - (a+b)\,i(n) = A'$$

Where, $A' = \sqrt{3}\ Em \left| Sin\ (\theta - 2\pi n - \beta + \frac{\pi}{6}) \right|_{2\pi n}^{2\pi n + \frac{\pi}{3}}$

$$+ \frac{\pi}{3}\ (Vd - 2\ V_{fwd})$$

$$= \sqrt{3}\ Em \left\{ Sin\ (\frac{\pi}{2} - \beta) - Sin\ (\frac{\pi}{6} - \beta) \right\} + \frac{\pi}{3}\ (Vd - 2V_{fwd})$$

$$= \sqrt{3}\ Em\ \ 2\ Sin\ \frac{\pi}{6}\ Cos\ (\frac{\pi}{3} - \beta) + \frac{\pi}{3}\ (Vd - 2\ V_{fwd})$$

In the interval 1-2, the valve 4 is 'ON', therefore

$$a \frac{di}{d\theta} + b\ \frac{di_1}{d\theta} = e_1 + Vd - 2\ V_{fwd}$$

$$= \sqrt{3}\ \ Em\ Cos\ (\theta - 2\pi n - \beta + \frac{\pi}{6} - \frac{4\pi}{6}) + Vd - 2\ V_{fwd}$$

$$= \sqrt{3}\ \ Em\ Cos\ (\theta - 2\pi n - \beta - \frac{\pi}{2}) + Vd - 2\ V_{fwd}$$

Limits of integration are:

$\theta_1 = 2\pi n + \frac{\pi}{3}$ to $\theta_2 = 2\pi n + \frac{4\pi}{6}$ for the boundary values for the currents i and i_1. After integrating the above we get:

$$(a+b)\ i'' - a\ i' = B' \text{ -------(18)}$$

Where,

$$B' = 2\sqrt{3}\ Em\ Sin\ \frac{\pi}{6}\ .\ Cos\ \beta + \frac{\pi}{6}\ (V_d - 2\ V_{fwd})$$

$$= \frac{\pi}{3} \left\{ \frac{3\sqrt{3}}{\pi}\ Em\ \ Cos\ \beta + V_d - 2\ V_{fwd} \right\}$$

Eqn.(18) and eqn. (9) coincide. This is expected.

For the rest of the intervals, analogous equations are obtained as follows:

$$\left.\begin{array}{l} i^{I} - i(n) = A \\ i^{II} - i^{I} = B \\ i^{III} - i^{II} = B \\ i^{IV} - i^{III} = B \\ i^{V} - i^{IV} = B \\ i(n+1) - \lambda i^{V} = B \end{array}\right\} \text{ ------------(19)}$$

Where $\lambda = \frac{a}{a+b} = \frac{X + X_\gamma}{X + 2\,X_\gamma}$

$$A = \frac{A'}{a+b} = \frac{2\sqrt{3}\ Em\ \sin\frac{\pi}{6}\ \cos\left(\frac{\pi}{3} - B\right) + \frac{\pi}{3}\left(Vd - 2\,V_{fwd}\right)}{X + 2\,X_\gamma}$$

$$B = \frac{B'}{a+b} = \frac{\pi}{3}\left\{\frac{\frac{3\sqrt{3}}{\pi}\ Em\ \cos\beta + V_d - 2\,V_{fwd}}{X + 2\,X_\gamma}\right\}$$

By eliminations, i^{I}, i^{II}, i^{III}, i^{IV}, i^{V} from eqns (19)

We get,

$$i\ (n+1) - \lambda^5\ i(n) = \lambda^5\ A + \frac{1-\lambda^5}{1-\lambda}\ B \quad \text{------------} \quad (20)$$

and hence

$$i\ (n) = \left(\frac{\lambda^5 A}{1-\lambda^5} + \frac{1}{1-\lambda}\ B\right)\left(1-\lambda^{5n}\right) + i\ (0)\ \lambda^{5n} \quad \text{-----} \quad (21)$$

<u>EXAMPLE</u>:-

The transient behaviour is illustrated by an example with the following assumed values:-

$X = 0.66$ p.u. $\quad X_\gamma = 0.33$ p.u. $\quad Em = 1.047$ p.u

$Vd = 0.85$ p.u. $\quad \beta = 45^{o}$

From these assumed values A & B are calculated from their expressions and are found to be 0.532 and 0.1785 respectively. Let the current i(n) during steady state operation be 1 p.u.

At $n = o$, $i = i(o) = 1.00$ p.u.

At $n = 1$, $i = i^{I}$, $\quad n = 4$, $i = i^{IV}$

$n = 2$, $i = i^{II}$ $\quad n = 5$, $i = i^{V}$

$n = 3$, $i = i^{III}$ $\quad n = 6$, $i = i\ (n+1)$

From the eqn.(21) the current i(n) is calculated for the values of n = 1, 2, 3, 4, 5 and 6. Then the reactive power required for the above points for V_o = 1 p.u. and β = 45° and δ = δ_o = 10° is calculated.

The results obtained are shown in the Table :

n =	0	1	2	3	4	5	6
i(n) p.u	1.00	0.468	0.835	0.871	0.879	0.8793	0.88
Pr(p.u)	0.505	0.2364	0.422	0.44	0.443	0.4434	.4443

Relationships between n vs. i(n) and n vs. Pr have been shown by curves (c) and (d) respectively in Fig.(5.6).

5.4. <u>CONCLUSION</u>:

(i) By forming (in accordance with the second Kirchoff's law) and solving the difference equation in the circuits under consideration, the discrete values of the output current in the transient behaviour have been obtained. The cases dealt govern all possible disturbances, viz. different changes of the e.m.f. at the input and output of the convertor and also disturbances of normal operationsuch as arc backs, breakdown and misfiring.

(ii) The solution of the linear difference equation gives the discrete values of the output current at instants of firing of the valves throughout the transient behaviour.

(iii) The difference equation is linear if β_n = constant or if β_n = f(n).

In the cases when $\beta_n = f(i)$, the difference equation is non-linear.

(iv) Graph nos. (5.4, 5.5, 5.6) drawn between i(n) and n for all the four cases, illustrate the nature of the output current during the transient behaviour for a 6-phase bridge invertor within the limits of assumptions made.

CONCLUSIONS

In this work an attempt has been made to discuss some important aspects of reactive power consumption required by an invertor for stable operation. Also transient behaviour of output current has been analysed under different conditions. A brief summary of background and present status of the problem has been given. Analytical expressions for reactive power demand and transient current have been derived.

Effect of different parameters on the reactive power demand has been studied. The reactive power demand varies with load conditions and system parameters. It has been studied that when load reactive power is zero, the reactive power demand is not much under normal range of operation. As the load increases, the reactive power demand increases and beyond active load of 0.85 p.u., the rate of increment of reactive power requirement is large. Invertors, however, may not be operated at such a high load and hence it is not difficult to meet the reactive power demand under normal range of operation.

Faults on the a.c. side of the invertor decreases the a.c. voltage and increases the direct current and therefore reactive power demand increases. It is seen that under such cases, the reactive power demand is less in case of compounded invertor than that in case of uncompounded invertor. It is observed that the reactive power demand in fault condition is very large.

By connecting filter circuits or static capacitors to the secondary winding of the convertor transformer, appreciablo improvemont in the commutation anglo and saving in reactive-power consumption is obtainod. It is observed that in tho case of filter circuits, saving is more than in tho case of static capacitors. In caso of tunned circuits tho peak value of the voltago is incroasod because of tho superimposod harmonics. Therefore, tho voltago stress on the valve will bo increased, thereby reducing the rating and sizo of tho valves. There is no such advantage in tho caso of bank of static capacitors. An invertor with filter circuits can be oporated stably for all values of currents, but in tho caso of connected static capacitors, the invertors can operate stably only for highor values of current. Automatic tunning arrangements for the filter circuits aro to be provided to allow for variation in supply frequency. No doubt, the cost of filter circuits and automatic tunning arrangements will be much moro than the cost of capacitors alone, but it is expectod that due to above mentioned advantages, the filtor circuits will replace static capacitors in not too distant future.

In analysing tho transient behaviour, mothod of difference equations has been adopted. By forming and solving the differenco equations in circuits undor considoration, the discrete values of output current throughout the transient behaviour have boen obtained. Different curves drawn show the nature of variation of output curront during the transiont process for a six-phase invertor within the limits of assumptions modo.

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