EVALUATION OF UNIT SCHEMES FOR HVDC CONVERTER STATIONS

A THESIS

PRESENTED TO

THE FACULTY OF GRADUATE STUDIES

THE UNIVERSITY OF MANITOBA

IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

ELECTRICAL ENGINEERING

by

DIDAR SINGH BAJWA

FEBRUARY, 1976.

"EVALUATION OF UNIT SCHEMES FOR
HVDC CONVERTER STATIONS"

by

DIDAR SINGH BAJWA

A dissertation submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

ABSTRACT

Advantages of HVDC transmission over a.c. transmission are discussed. Unit-type of connections (Single-Block and Double-block) for the converter layout in HVDC transmission are discussed in detail. Due to the intermittent operation of the converter, characteristic harmonic currents of the order of h = pn $\pm$ 1 are generated on a.c. side of converter. In unit type of connections, harmonics are allowed to flow into the generator. The magnitude and phase angle of harmonics with respect to respective line to neutral voltage are calculated. A simplified theoretical method is developed for calculation of additional losses in the stator and rotor circuits of a generator with any number of damper circuits, due to flow of harmonics. Results of calculations of additional losses in the stator and rotor circuits of a simplified model of a generator with one damper circuit on each axis are presented.

Derating factor for a generator of conventional design to be used for unit-connections is calculated. There seems to be no need to derate the generator for Double-block connection. For Single-Block connection, derating of the generator is needed.

Technical and economic evaluation of unit schemes as compared to conventional schemes is made. Approximate savings in cost of the converter station in unit arrangement as compared to conventional of 25 - 30% is expected.

ACKNOWLEDGEMENTS

The author would like to express his appreciation and deepest gratitude to Dr. R.M. Mathur for suggesting the thesis topic, his esteemed guidance in the preparation of this thesis, and financial support.

Special thanks are due to Professor M.Z. Tarnawecky and Dr. P.C.S. Krishnayya, Teshmont Consultants Ltd., who were always willing to assist in every possible way.

Thanks are also due to Manitoba Hydro for allowing the use of data from their system. Particular thanks are due to Maria T. Graceffo and Judith Moroz Bade for their tireless efforts in typing of the manuscript.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS

All the quantities below are in the p.u. values unless otherwise specified.

a, b, c	Phase sequence
e_a, e_b, e_c	Instantaneous voltages of phase a, b and c, respectively, with respect to neutral
E_{max}	Crest value of line to neutral voltage
E_{LN}	R.M.S. value of line to neutral voltage
h	Characteristics harmonic order
i_h	Instantaneous value of hth harmonic current
i_{ah}, i_{bh}, i_{ch}	Instantaneous value of harmonic current phases a, b and c, respectively
i_{hd}, i_{hq}	Harmonic current component along d and q axis respectively
I_{dc}	Average value of direct current
I_{L1}	R.M.S. value of the fundamental component of a.c. line current
I_h	R.M.S. value of hth harmonic current
$\hat{I}_{s2}$	Crest value of short circuit current during commutation
I_{dpn}, I_{qpn}	Vectorial sum of the transformed stator currents of the order of $h = pn \pm 1$ along d-axis and ω-axis respectively
I_{fpn}	R.M.S. value of induced current of pnω frequency in the field circuit
I_{kdpn}, I_{kqpn}	R.M.S. value of induced current of pnω frequency in the kth damper circuit on d-axis and ω-axis respectively
I_{1n}	New current rating after derating

k Number of damper circuit

L Inductance of transformer

p Pulse number of the rectifier

r_d, r_q Resistance of d and q coil respectively

r_{ff} Resistance of the field winding

r_{11d}, r_{11q} Resistance of d-axis and q-axis damper coil

r_{en}, r_{eh} Equivalent resistance of generator for normal operation and operation with harmonics

V_d Average value of direct voltage

x_d, x_q Direct-axis and quadrature-axis reactance of the generator

x_d'', x_q'' Direct-axis and quadrature-axis sub-transient reactance of the generator

x_{ad}, x_{aq} Armature magnetizing reactance along d-axis and q-axis

x_ℓ Armature leakage reactance

x_{fd} Leakage reactance of the field winding

x_{ff} Total reactance of the field winding

x_{1d}, x_{1q} Leakage reactance of d-axis and q-axis damper coil

x_{11d}, x_{11q} Total reactance of d-axis and q-axis damper coil

x_{fkd}, x_{kfd} Mutual reactance between field circuit and kth damper circuit on d-axis

x_{dkd} Mutual reactance between d-coil and kth damper circuit on d-axis

α Delay angle of rectifier in radians

u Overlap or commutation angle of rectifier in radians

δ	$\alpha + u$
δ_m	Load angle of the generator
ϕ	Angle between generator terminal voltage and fundamental component of a.c. current (Power Factor angle)
ϕ_h	Phase angle of hth harmonic with respect to line to neutral voltage
ω	Angular frequency in radians/sec
t	time

CHAPTER 1

INTRODUCTION

1.1 HVDC Transmission

In general terms, High Voltage Direct Current (h.v.d.c.) transmission involves the transmitting of power between two a.c. terminals, first by converting a.c. to d.c. and then d.c. to a.c.. At present, the transmission of electrical energy from power plants by h.v.d.c. overhead lines is restricted to cases where power must be transmitted over long distances. A few situations where h.v.d.c. provides an attractive alternative are discussed below.

(a) HVDC can be economically attractive, where large volumes of water can be used to produce inexpensive electricity which may prove to be cheaper than the locally produced electricity, in spite of the cost of transmitting it over long distances. Specific examples are [1,4] Nelson River Scheme, 2 x 1620 MW, $\pm$ 450 kV transmitting over 900 km and one in Africa[2] for 1920 MW, $\pm$ 533 kV transmitting over 1400 km.

(b) Mine mouth generation: where the cost of transporting electricity is cheaper than transporting the raw material (fossil fuel) itself. Particular example is Ekibastuz centre plant in Russia which is in the planning stage being built for ultimate generation of 6000 MW, $\pm$ 750 kV over 2500 km. In the above cases, the h.v.d.c. enjoys its economic superiority over a.c. due to the long distances involved.

(c) HVDC link allows the additional load to be fed without raising the short circuit capacity of the system beyond the interrupting capability of the existing circuit-breakers. Also, it is preferable where the conditions in the densely populated areas require underground cables, due to the non-availability of right of way for overhead lines.

(d) Another attractive application of h.v.d.c. power infeed is in pumped-storage schemes. Under certain circumstances, h.v.d.c. enables the frequency at the power station end to be made variable, thus permitting pump turbines to be operated about the optimum efficiency in both directions, i.e. at various speeds, and therefore bring about a certain improvement in their cost effectiveness.

(e) Also, hydro-electric generating stations, when connected to a load centre through long a.c. lines, must have generators with abnormally low transient reactances or abnormally high moment of inertia in order to raise the stability limit. These restrictions raise the cost of the generators and could be avoided if d.c. transmission is used.

(f) HVDC transmission has been competitive with a.c. only when large amounts of power are to be transmitted over long distances. D.c. transmission enjoyed its economic superiority over a.c. only above certain distance, called break-even distance, below which a.c. is economical as shown in Fig. 1.1.

(g) For cables crossing bodies of water.

(h) For interconnecting a.c. systems having different frequencies, or where asynchronous operation is desired.

(i) Faster control of power and better utilization of the cross-section area of conductor, due to the absence of skin effect.

The main drawback of d.c. is the cost of its terminal equipment. If efforts are made to reduce the cost of the terminal equipment the break-even distance could be lowered to make HVDC more attractive. According to the available literature[3], break-even distances are approximately 830 km (515 miles) for overhead lines, 64 km (40 miles) for underground cables.

Some of the other disadvantages of HVDC transmission are increased reactive, corrosion of underground metallic parts, due to the use of ground return, interference with telephone circuits and generation of harmonics.

This thesis is devoted to the evaluation of unit schemes (where-ever it is applicable) for HVDC converter stations, and the calculation of the derating factor of generators due to the flow of harmonics.

1.2 Converter Layout

In conventional HVDC schemes, rectifiers are connected through converter transformers to a common a.c. bus which is fed by a group of generators. This arrangement is called a.c. collector system. An example of such an arrangement is the Nelson River Development[4]. Fig. 1.2 shows

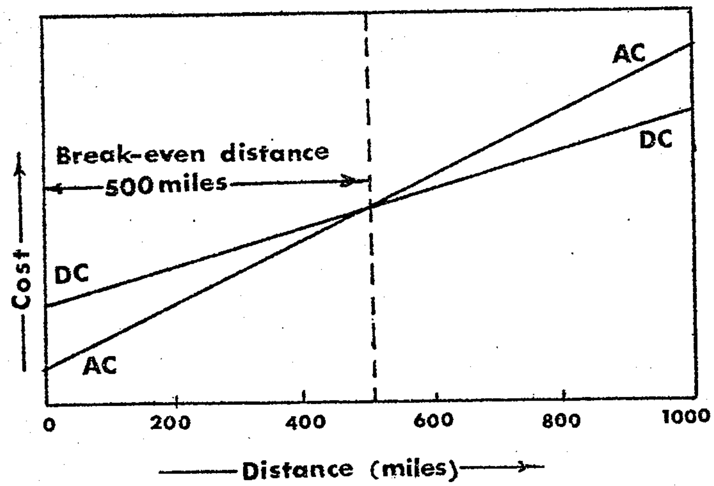


Fig 1·1 Comparative costs of ac and dc overhead lines verses distance

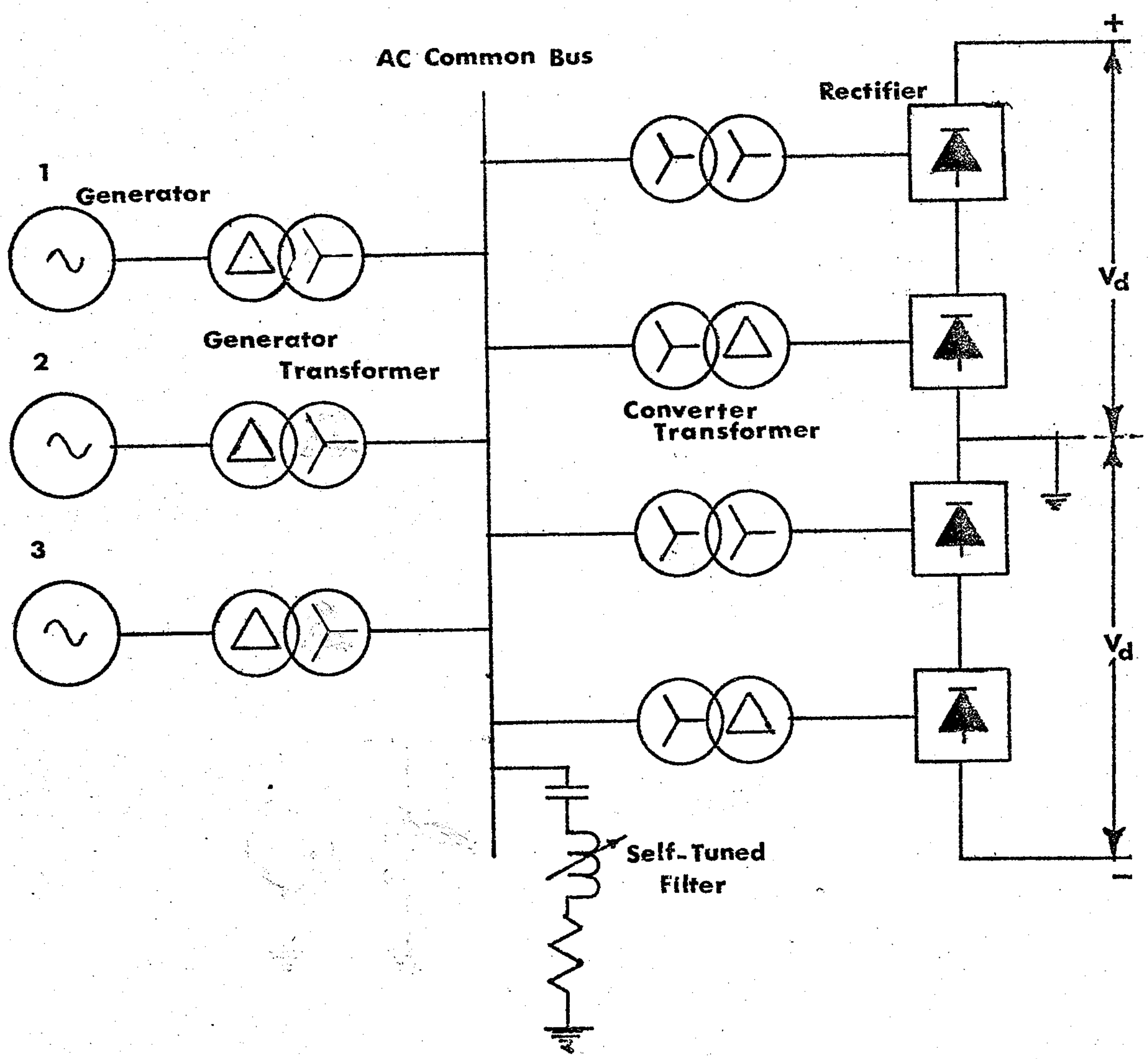


Fig 1.2 Conventional layout of converter stations

the basic features of the system by a single line diagram. Essentially it resembles a conventional a.c. system, where the outgoing circuits are modified for HVDC transmission. Filters are provided to absorb the harmonics as well as to keep the voltage of the a.c. common busbar sinusoidal. Conventional HVDC station has its certain drawbacks. First of all, the failure of a.c. filters or their going off-tune during certain fault conditions cause overstresses on the connected equipment and filters. Also associated with it are the problems of the stability of the generators and the provision of on-load tap-changers on the converter transformer. To overcome these problems, to reduce the cost of the terminal equipment and to improve the performance of the HVDC power stations, Unit or Block-type of connections have been suggested[2,5,6]. These types of connections are discussed in detail in this chapter.

1.3 Unit or Block Connection

Unit connections[5] are shown in Fig. 1.3. The important features of these connections are:

1. The converter station is to be located in close proximity to the generating station.
2. Only one transformer is to be used which serves as generator-converter transformer and is designed as a converter transformer. No tap-changers are provided.
3. A.c. harmonic filters are not provided.
4. The rectifiers used are 3 - ϕ, 6-pulse bridge rectifiers with controllable valves as are normally used in HVDC transmission.

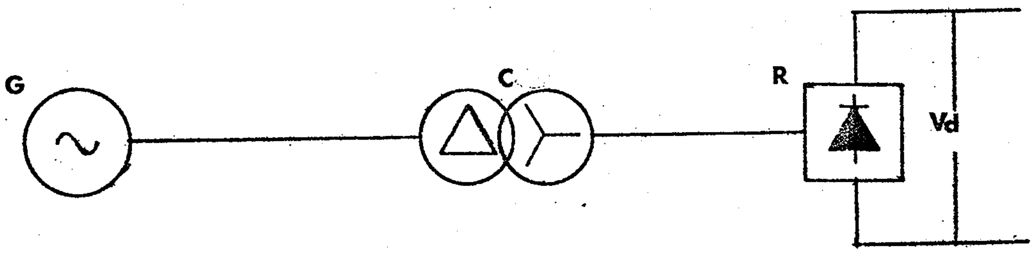
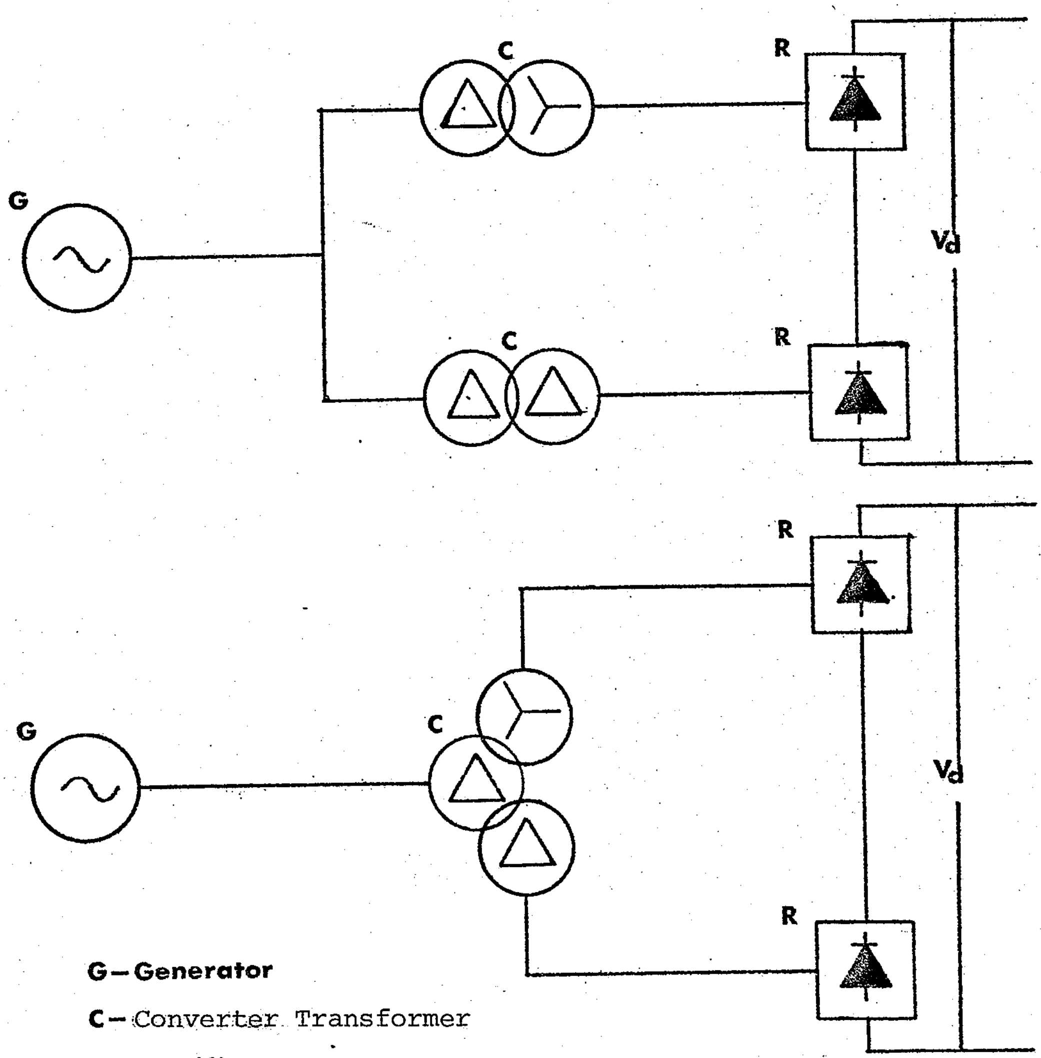


Fig 1·3 (a) Single-Block Connection
Single-line diagram



G – Generator
C – Converter Transformer
R – Rectifier

Fig 1·3 (b) Double-Block Connection
Single-line diagram

Single-Block (SB) connection operates on 6-pulse whereas Double-Block (DB) connection has 12-pulse operation.

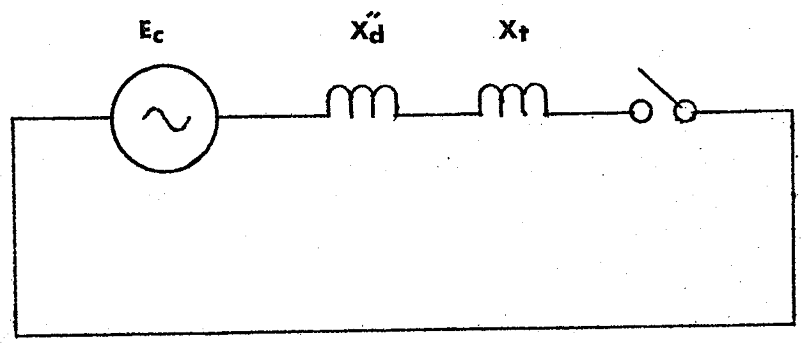
In the case of Single-Block connection (Fig. 1.3(a)), a single generator feeds a 3 - ϕ, 6-pulse bridge rectifier through a generator-converter transformer. In Double-Block connection (Fig. 1.3(b)), a single generator feeds a 12-pulse cascade connection of two bridge rectifiers through two separate two-winding transformers or through a single 3-winding transformer.

Due to the absence of filter circuits, the generator sustains a line to line short-circuit during commutation. The commutation reactance is the sum of transformer leakage reactance and the generator sub-transient reactance. The equivalent circuit representation of block connections is shown in Fig. 1.4. The most dominating factor in the design of Double-Block connections is the generator sub-transient reactance. For the satisfactory operation of the converter, the overlap angle of 30^{0} is reached for minimum delay angle of 10^{0} with the generator sub-transient reactance[5] of 0.24, together with the transformer leakage reactance of 0.1 p.u..

So the generator sub-transient reactance should not exceed 0.24 with a minimum delay angle of 10^{0}, for satisfactory operation.

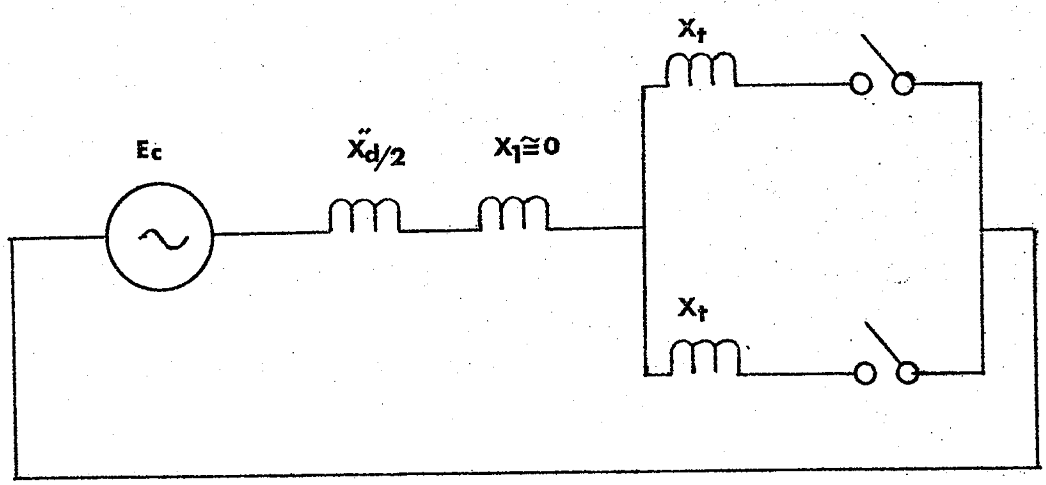
1.4 Advantages of Unit Connections

Disadvantages of the conventional arrangement are the advantages of unit arrangement. As indicated earlier, the transformer acts as a



$$X_c = X''_d + X_t$$

Fig 1·4(a) Equivalent circuit of Single-Block Connection



$$X_c = X''_{d}/2 + X_t$$

Fig 1·4(b) Equivalent circuit of Double-Block connection generator - converter transformer and hence only one transformation stage is required and therefore a saving in cost is achieved.

Fault in the harmonic filters in the case of a conventional scheme may cause the breakdown of the whole system and, of course, a headache to the utility engineers. There are no filter problems with the unit connection thus making the HVDC station far more independent of the frequency. This could be a blessed advantage where HVDC infeed is used for damping fluctuations in the power system, making better use of the stored energy in the rotating mass. Also in the case of pumped-storage schemes, there are no filters for readjustment for change-over to pumping operation at a different frequency.

In the case of filters as in conventional schemes, if power frequency, and therefore also the harmonics which are typical for static converters, become displaced, there is danger of resonance which could overload the filters, the generators and generator transformers.

Due to the elimination of a.c. common bus, there is a lot of saving in the switchyard space and equipment such as circuit-breaker between generator-transformer and a.c. bus and circuit-breaker between a.c. bus and converter transformer, etc.. However, the unit connections have certain limitations which are discussed below.

1.5 Disadvantages of Unit Connections

As there are no filters provided, the generators have to be over-dimensioned to absorb harmonics and supply the whole reactive power for the converter operation. Due to the higher effective commutation reactance, the ratio of no-load voltage to rated voltage on d.c. side increases, so the valves must be designed for higher overvoltages.

As regards reliability, unit connection (DB) suffers, due to the fact that if one bridge of a converter becomes faulty, the whole unit will have to be shut off thus losing the double output due to the rigid connection between the generator and converter-transformer but this is compensated by the reduced probability of the fault in the a.c. switchyard.

The main control system, which is quite complex in the case of a conventional scheme, could be considerably simplified.

Since the harmonics are not filtered, some telephone interference is expected but is minimized and is not alarming due to the close proximity of the converter station to the generating station.

1.6 General Objectives of Research

Due to the absence of harmonic filters in the unit connections, harmonics are of the order[1] of $(pn \pm 1)$ in the stator windings, where p denotes the pulse number and n is a positive integer. In this thesis in Chapter 2, the p.u. magnitude of each harmonic component, as well as its phase angle with respect to line to neutral phase voltage is calculated.

The harmonic currents of the order of $pn \pm 1$ induce currents of frequency pn in the rotor circuits. As these high frequency induced currents are confined to high resistance rotor surface paths, they cause considerable losses and hence rotor heating. These rotor losses have been calculated by Glebov[7], by applying the theory of forward and backward rotating fields.

Glebov's results, however, cannot be used directly because he has not specified all parameters for which the results are presented. In order to evaluate the underrating of the generators to allow the additional losses due to current harmonics in the machines detailed investigations are made in Chapter 3 and Chapter 4.

The evaluation of the unit schemes in comparison with the conventional schemes is made in Chapter 5. The conclusions of the findings are presented in Chapter 6.

CHAPTER 2

A.C. CURRENT HARMONICS

2.1 Analysis

In HVDC transmission, currents on the A.C. side of the converter are not of sinosoidal shape, due to the intermittent operation of the converter. The wave shape is however periodic and therefore can be analyzed into a mains frequency component and higher (multiple order) harmonics. The harmonics[1] are found to be of the order of:

$$h = pn \pm 1 \tag{2.1}$$

where, p - Pulse number of the converter (6 or 12 usually)

and n - is a +ve integer

Fig. 2.1 shows the schematic circuit for the analysis of a 6-pulse bridge converter. Fig. 2.2 shows the wave-shape of one half cycle of a line to neutral voltage and of the corresponding line current on the valve side of the converter transformer for single overlap, that is, for overlap not exceeding 60°. The origin of the angle $\theta = \omega t$ is at the positive crest of the voltage wave. The next half cycle is exactly the same except that the instantaneous values of voltages and currents are negative.

The instantaneous value of the voltage is given by

$$e_a = E_{max} \cdot \cos\theta \tag{2.2}$$

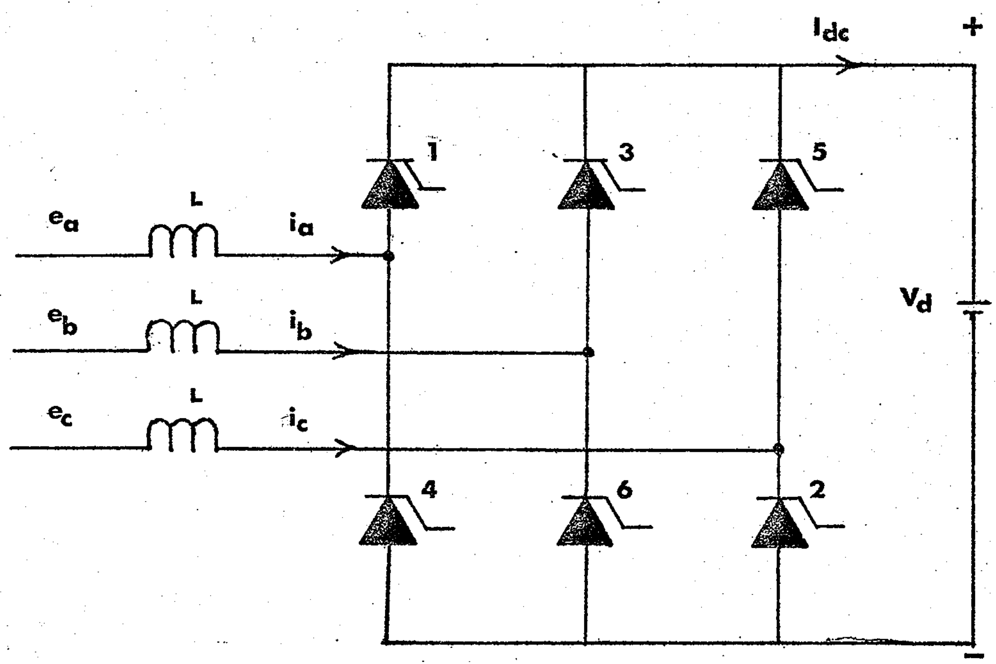


Fig 2·1 Bridge-Connected Rectifier

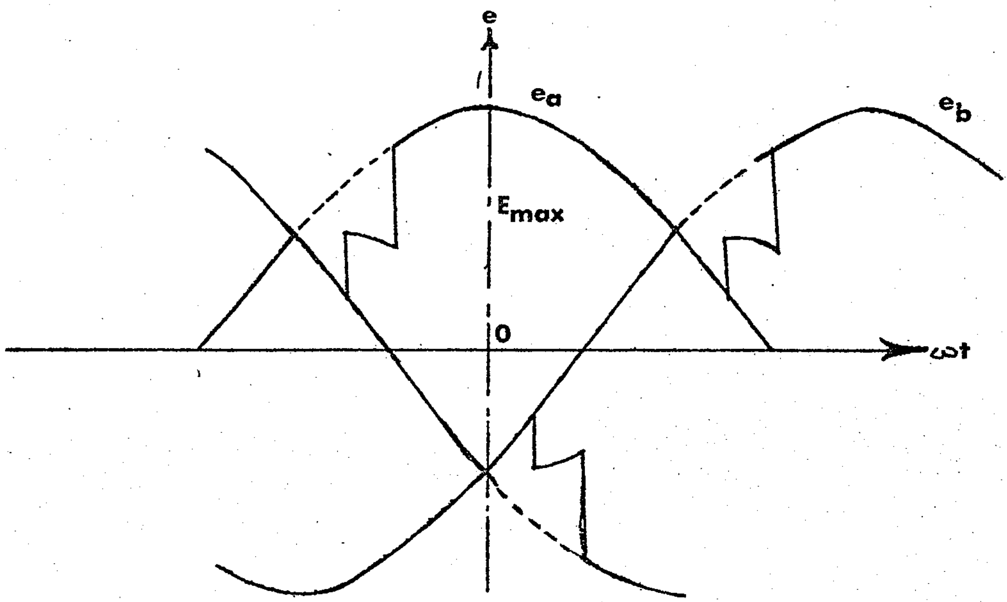


Fig 2·2(a) Line to neutral voltages

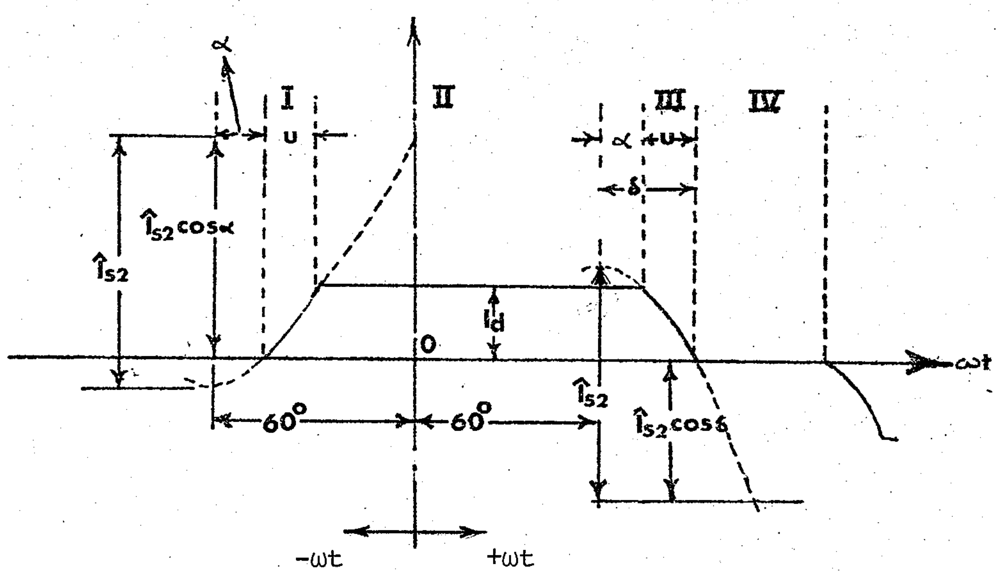


Fig 2·2 (b) Current in phase a

For the other two phases b & c, the currents as well as voltages lag those of phase a by 120° and 240° respectively.

For the analysis, phase 'a' current wave-shape is divided into four segments I to IV as shown in Fig. 2.2 (b). The instantaneous value of the current in each segment is given by the following equations (Kimbark[1], Appendix A, Page 484)

Segment	Limits	Equation	
I	$\alpha-60^\circ < \theta < \delta-60^\circ$	$i_I = \hat{I}_{s2}[\cos\alpha - \cos(\theta + 60^\circ)]$	(2.3)
II	$\delta-60^\circ < \theta < \alpha+60^\circ$	$i_{II} = \hat{I}_d = \hat{I}_{s2}(\cos\alpha - \cos\delta)$	(2.4)
III	$\alpha+60^\circ < \theta < \delta+60^\circ$	$i_{III} = \hat{I}_{s2}[\cos(\theta - 60^\circ) - \cos\delta]$	(2.5)
IV	$\delta+60^\circ < \theta < \alpha+120^\circ$	$i_{IV} = 0$	(2.6)

where, $\hat{I}_{s2}$ = crest value of S.C. current between any two phases during commutation

$$= \sqrt{3}\, E_{max}/2\omega L$$

The magnitude and phase angle of different harmonics are determined by representing the current wave by fourier series. The complex form of such a series is

$$F(\theta) = \sum_{h=-\infty}^{+\infty} A_h \underline{/h\theta} \qquad (2.8)$$

where, $$A_h = \frac{1}{2\pi} \int_{-\pi}^{\pi} F(\theta)\, \underline{/-h\theta}\, d\theta \qquad (2.9)$$

and $\underline{/h\theta} = e^{jh\theta} = \cos(h\theta) + j\sin(h\theta)$

The wave shape being symmetrical, the value of A_0 component is zero.

Also, for the wave-shape in question since $F(\theta) = -F(\theta + \pi)$ only odd harmonics exist.

Therefore equation 2.9 can be rewritten as

$$A_h = \frac{1}{\pi} \int_0^{\pi} F(\theta) \, \underline{/-h\theta} \, d\theta \tag{2.10}$$

The crest value and phase of the hth harmonic are given by

$2A_h$

$$\sqrt{2}\, I_h = \frac{2}{\pi} \int_{\alpha-60^\circ}^{\alpha+120^\circ} i(\theta) \, \underline{/-h\theta} \, d\theta \tag{2.11}$$

Where I_h is the complex r.m.s. value of the hth harmonic current and $i(\theta)$ is the value of the instantaneous current. The phase of the current is expressed as advance with respect to the line to neutral voltage.

Substituting the value of $i(\theta)$ in all four segments and applying the appropriate limits for integration

$$\sqrt{2}\, I_h = \frac{2}{\pi}\Big[\int_{\alpha-60^\circ}^{\delta-60^\circ} \hat{I}_{s2}\{\cos\alpha - \cos(\theta + 60^\circ)\} \, \underline{/-h\theta} \, d\theta$$

$$+ \int_{\delta-60^\circ}^{\alpha+60^\circ} \hat{I}_{s2}(\cos\alpha - \cos\delta) \, \underline{/-h\theta} \, d\theta$$

$$+ \int_{\alpha+60^\circ}^{\delta+60^\circ} \hat{I}_{s2}\{\cos(\theta - 60^\circ) - \cos\delta\} \, \underline{/-h\theta} \, d\theta \Big]$$

or $$I_h = \frac{\hat{I}_{s2}}{\sqrt{2}\pi}\Big[\int_{\alpha-60^\circ}^{\delta-60^\circ} \{2\cos\alpha - 2\cos(\theta + 60^\circ)\}\ \underline{/-h\theta}\ d\theta$$

$$+ \int_{\delta-60^\circ}^{\alpha+60^\circ} 2(\cos\alpha - \cos\delta)\ \underline{/-h\theta}\ d\theta$$

$$+ \int_{\alpha+60^\circ}^{\delta+60^\circ} \{2\cos(\theta - 60^\circ) - 2\cos\delta\}\ \underline{/-h\theta}\ d\theta\Big]$$

or $$I_h = \frac{\sqrt{2}}{\pi}\hat{I}_{s2}\sin(h60^\circ)\Big[\frac{\underline{/-(h+1)\alpha} - \underline{/-(h+1)\delta}}{(h+1)} - \frac{\underline{/-(h-1)\alpha} - \underline{/-(h-1)\delta}}{(h-1)}\Big] \qquad (2.12)$$

The details of the calculations are shown in Appendix A. The derivation in equation (2.12) is only valid for harmonics of characteristics order h. Characteristics harmonics are those of orders given by equation (2.1).

In equation (2.12), the phase of the harmonic current is with respect to respective line neutral voltage and not with respect to respective commutation voltage as defined by Kimbark[1].

$$\sin(h60^\circ) = -\frac{\sqrt{3}}{2} \text{ for } h = 5, 11, 17, \ldots\ldots \text{ etc.}$$

$$= \frac{\sqrt{3}}{2} \text{ for } h = 7, 13, 19, \ldots\ldots \text{ etc.} \qquad (2.13)$$

From rectifier theory

$$\hat{I}_{s2} = \frac{I_d}{\cos\alpha - \cos\delta} \tag{2.14}$$

$$I_{L1} = \frac{\sqrt{6}}{\pi} I_d \cong I_{L10} \tag{2.15}$$

where, I_{L1} = fundamental rms a.c. current at any overlap

I_{L10} = fundamental rms a.c. current at no overlap

$I_{L1} = I_{L10}$ at $u = 0^\circ$; I_{L1} is however, approximately equal to I_{L10} for normal operating values of u. The error is less than 1% for $u = 30^\circ$ and less than 4% for $u = 60^\circ$.

Substituting for I_d in equation (2.14) from equation (2.15)

$$\hat{I}_{s2} = \frac{\sqrt{\pi}}{6} \frac{I_{L1}}{\cos\alpha - \cos\delta} \tag{2.16}$$

Let $\cos\alpha - \cos\delta = D$ (2.17)

Substituting in equation (2.12) we get

$$I_h = \pm \frac{I_{L1}}{2hD} \left[\frac{\underline{/-(h+1)\alpha} - \underline{/-(h+1)\delta}}{(h+1)} - \frac{\underline{/-(h-1)\alpha} - \underline{/-(h-1)\delta}}{(h-1)} \right] \tag{2.18}$$

+ sign for h = pn + 1

- sign for h = pn - 1

Equation (2.18) gives the magnitude and phase angle of the harmonic currents of the characteristics order h, phase being referred to respective line to neutral voltage. Comparison of the results of equation 2.18 with those obtained by Kimbark show that phase angle of the harmonics is with respect to respective line to neutral voltage and not with respect to commutating voltage. It is stressed that the phase angle of the harmonics h = pn - 1 will have a phase shift of 180° as obtained from the expression in his book (equation 23, page 305). It appears that his main concern has been the magnitudes of harmonics and not the phase angle, hence the neglect of a negative sign.

Equation 2.18 may be rewritten as

$$I_h = \pm \frac{I_{L1} F_1}{2hD} \tag{2.19}$$

where $F_1 = \left[\frac{\underline{/-(h+1)\alpha} - \underline{/-(h+1)\delta}}{(h+1)} - \frac{\underline{/-(h-1)\alpha} - \underline{/-(h-1)\delta}}{(h-1)}\right]$

The p.u. magnitude of these harmonics and their phase angle are computed by a computer program (Appendix C) for SB and DB connections. Figs. 2.3 to 2.14 shown the variation of the harmonics magnitudes for different values of out-put direct current for SB connection and Figs. 2.15 to 2.20 for DB connection.

It is very difficult to compare the magnitude of a particular harmonic component for the SB and DB connection for a particular operating condition, because the harmonic magnitude depends upon the delay angle and commutation reactance. In all above calculations, for a particular value of α, the change in I_{dc} is brought by changing the overlap angle u keeping the secondary voltage and commutation reactance constant.

2.2 Per Unit Representation

To be consistent with the technical literature, and present the results of this thesis in an acceptable form, all the quantities are used in their p.u. form in the subsequent chapters. The base parameters for all the quantities are defined as below.

(a) A.C. Side

Power: $P_a = 3\, E_{LN}\, I_{L1} \cos\phi$ (2.20)

Voltage: E_{LN} = Rated line to neutral voltage (r.m.s. value)

Current: I_{L1} = Rated fundamental a.c. line current (r.m.s. value)

(b) D.C. Side

Power: $P_d = V_d I_d$ (2.21)

Voltage: V_d = Rated D.C. voltage

Current: I_d = Rated D.C. current

From rectifier theory

$$V_d = \frac{3\sqrt{6}}{\pi} \left(\frac{\cos\alpha + \cos\delta}{2}\right) E_{LN} \tag{2.22}$$

and

$$I_{L1} \cong \frac{\sqrt{6}}{\pi} I_d \tag{2.24}$$

Using the same power base on both A.C. and D.C. side

$$\underset{\sim}{P}_d = \underset{\sim}{P}_a \tag{2.25}$$

$$\underset{\sim}{I}_d = \underset{\sim}{I}_{L1} \tag{2.26}$$

$$\underset{\sim}{V}_d = \underset{\sim}{E} \cos\phi \tag{2.27}$$

The curly underline represents the p.u. quantity. From section 2.1, the per unit harmonic current is therefore given by

$$\underset{\sim}{I}_h = \frac{I_h}{I_{L1}} = \pm \frac{F_1}{2hD} \tag{2.28}$$

From here on all parameters are represented only in p.u. therefore no curly underline will be marked.

I_h can also be represented by a cosine function as

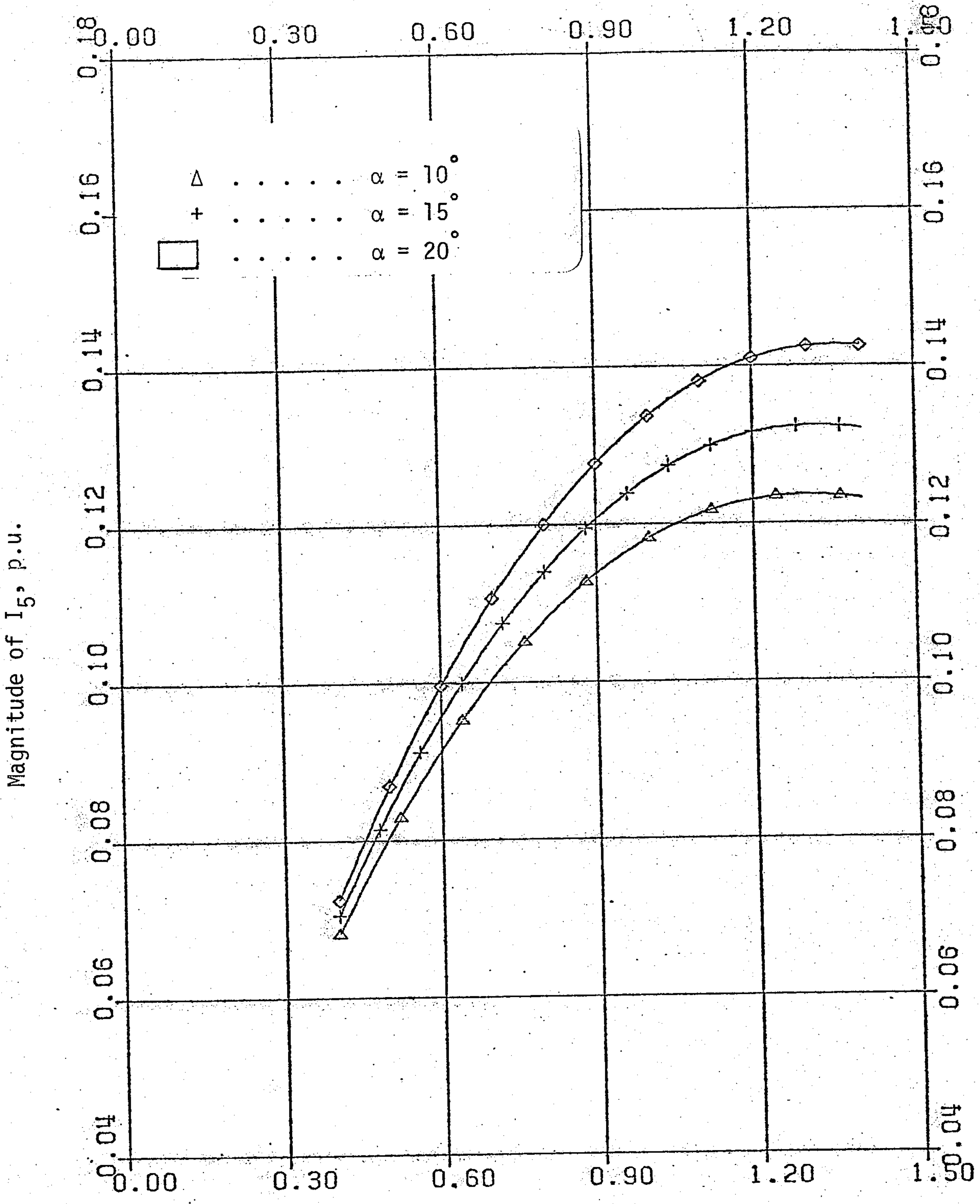
$$i_h = \sqrt{2}\, I_h \cos(h\theta - \phi h) \tag{2.29}$$

where, ϕh = phase angle with respect to line to neutral voltage.

Double Block Connection

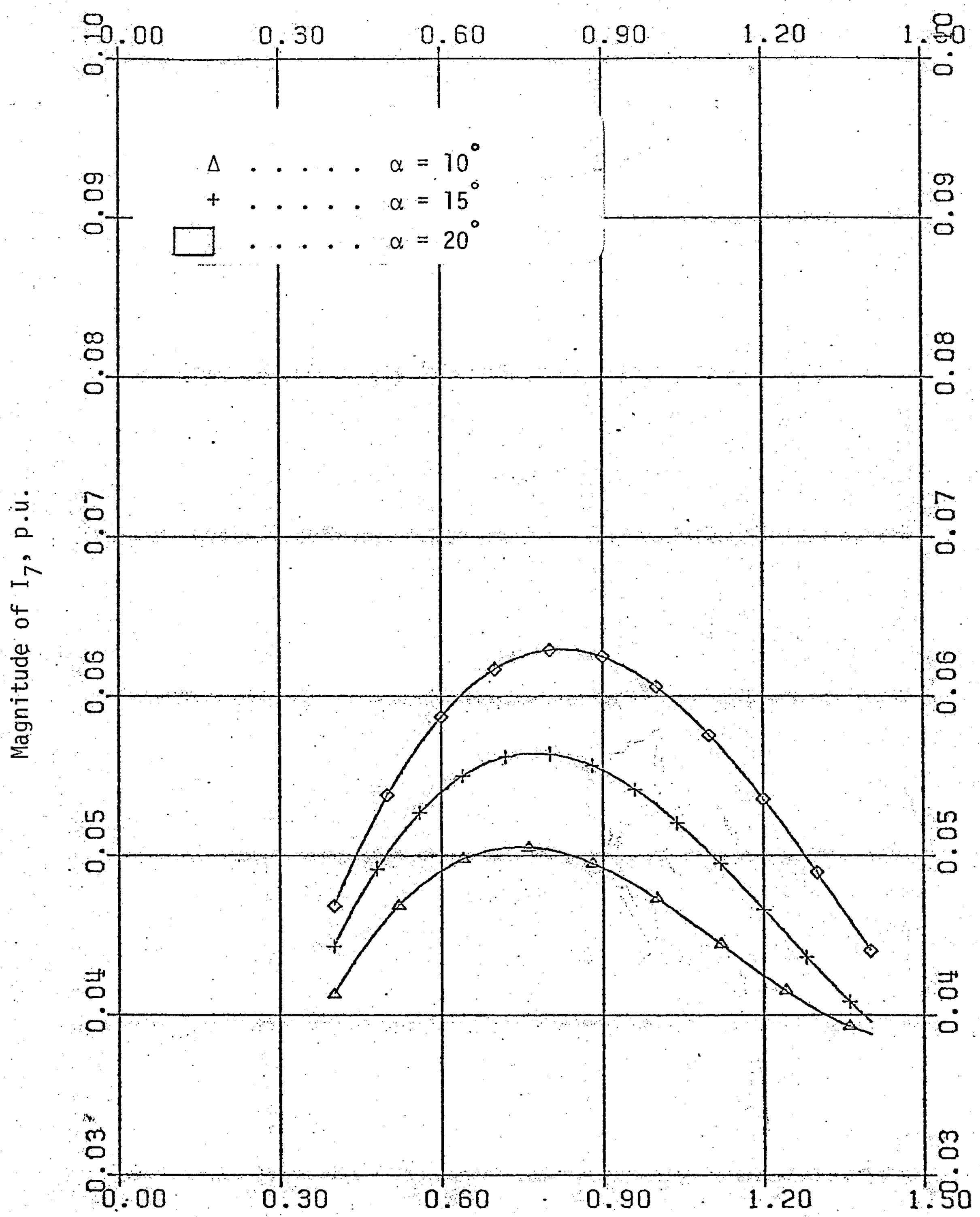
DB connection works in a 12-pulse operation and HVDC converter is composed of two 6-pulse groups fed from sets of valve-side transformer windings having a phase difference of 30° between the fundamental voltages, (i.e. one transformer is connected $\Delta - \Delta$ and the other transformer $\Delta - Y$). Currents of orders 5, 7, 17, 19, etc., circulate between the two banks of transformers, but do not enter the a.c. line. If there are two valve windings and one network windings on each transformer, these harmonics appear only in the valve windings.

The p.u. magnitude of these harmonics and their phase angles are computed for x_c = 0.24 p.u. for DB connection and x_c = 0.36 p.u. for SB connection, where x_c denotes the commutation reactance.



Direct Current, I_{dc} in p.u.

Fig. 2.3 Magnitude of 5th harmonic current as a function of I_{dc} in SB connection.



Direct Current, I_{dc} in p.u.

Fig. 2.4 Magnitude of 7th harmonic current as a function of I_{dc} in SB connection.

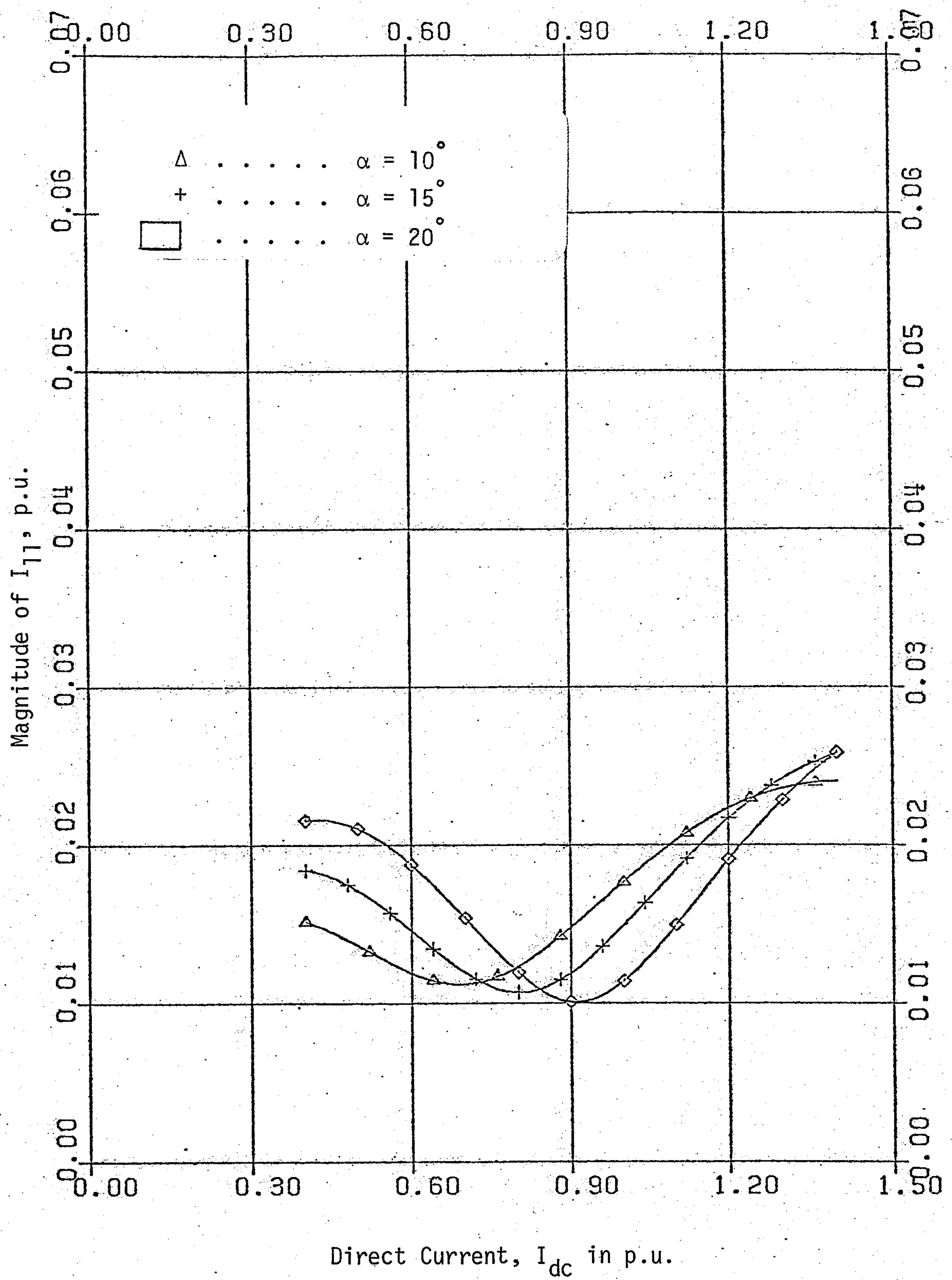
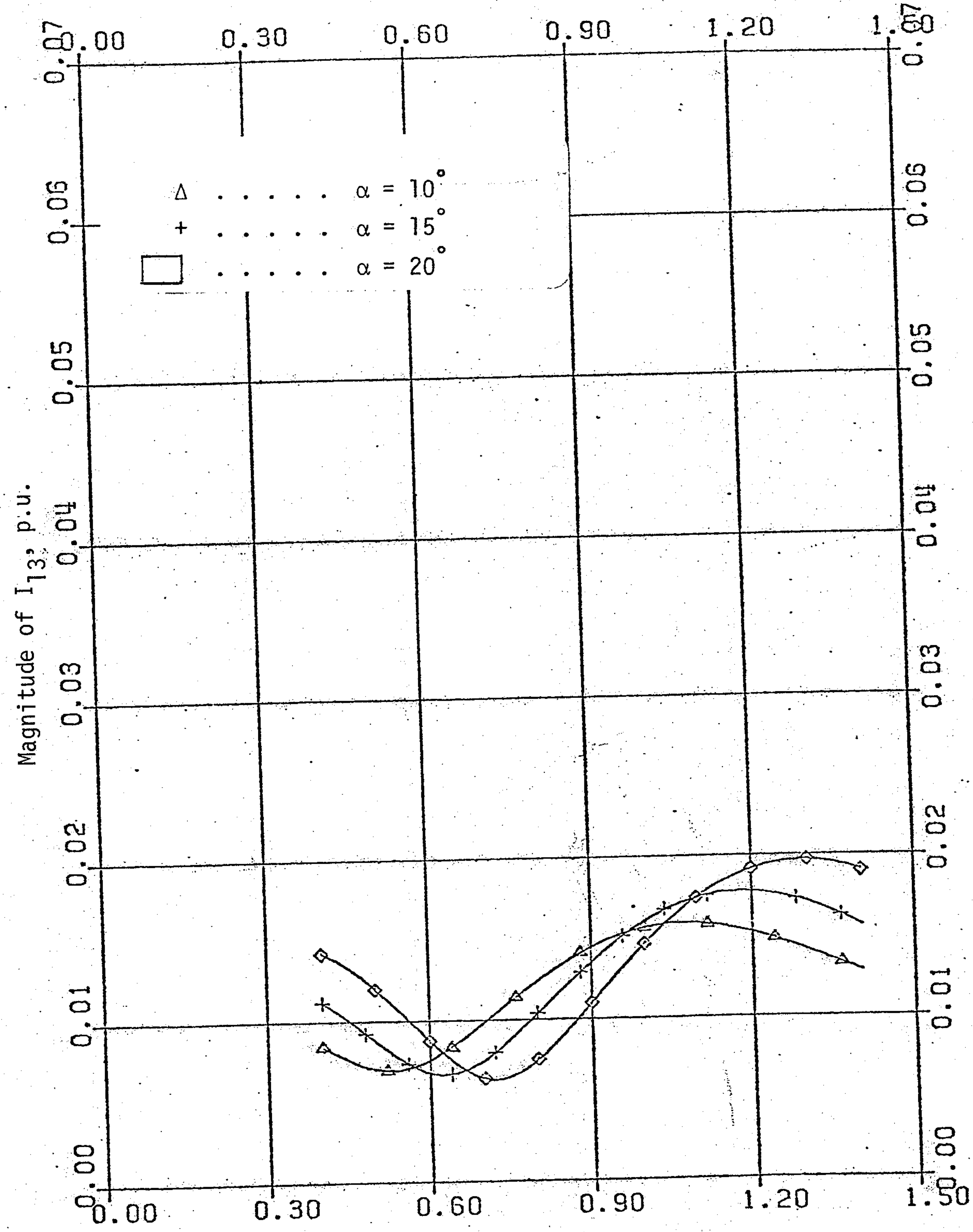
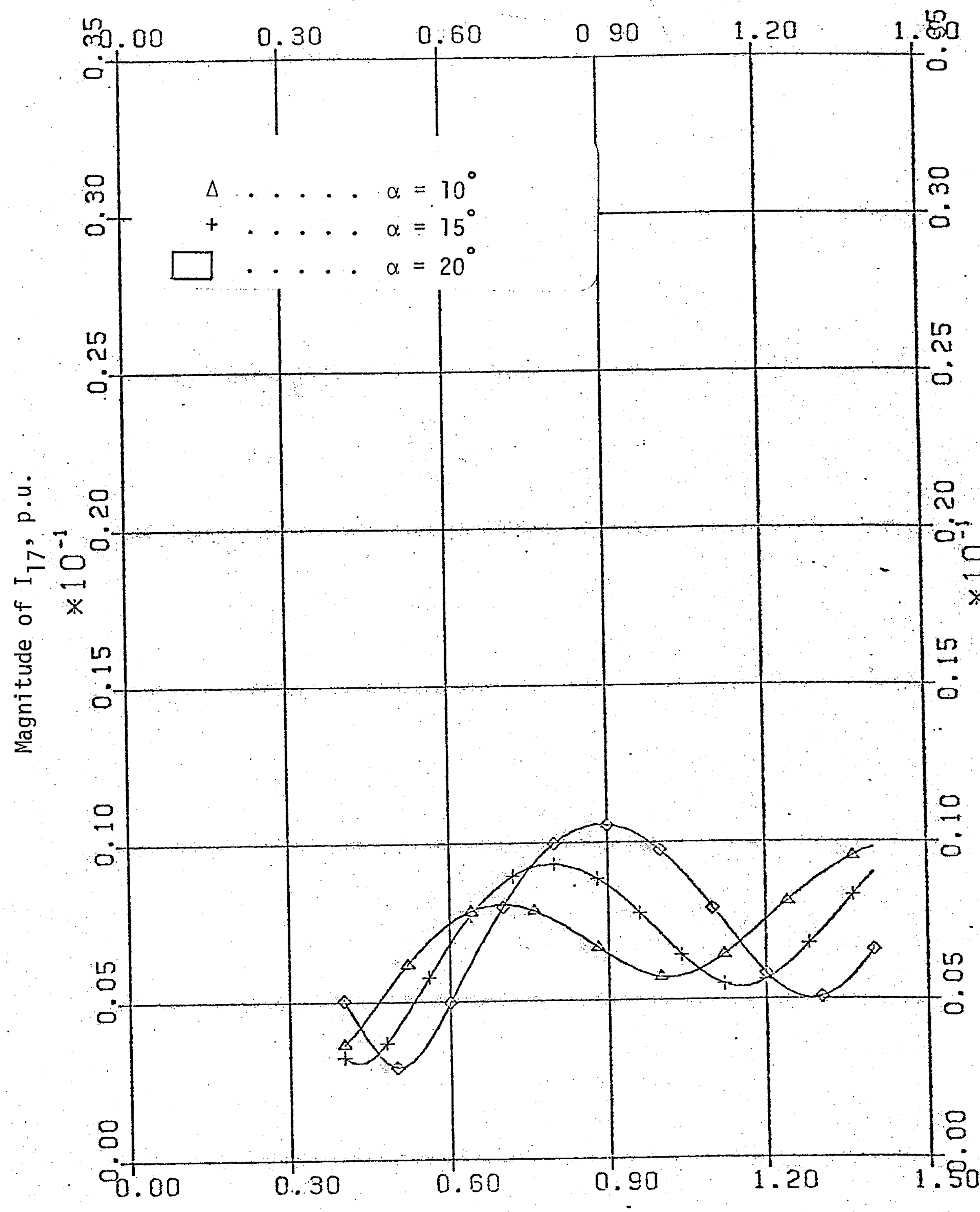


Fig. 2.5 Magnitude of 11th harmonic current as a function of I_{dc} in SB connection.



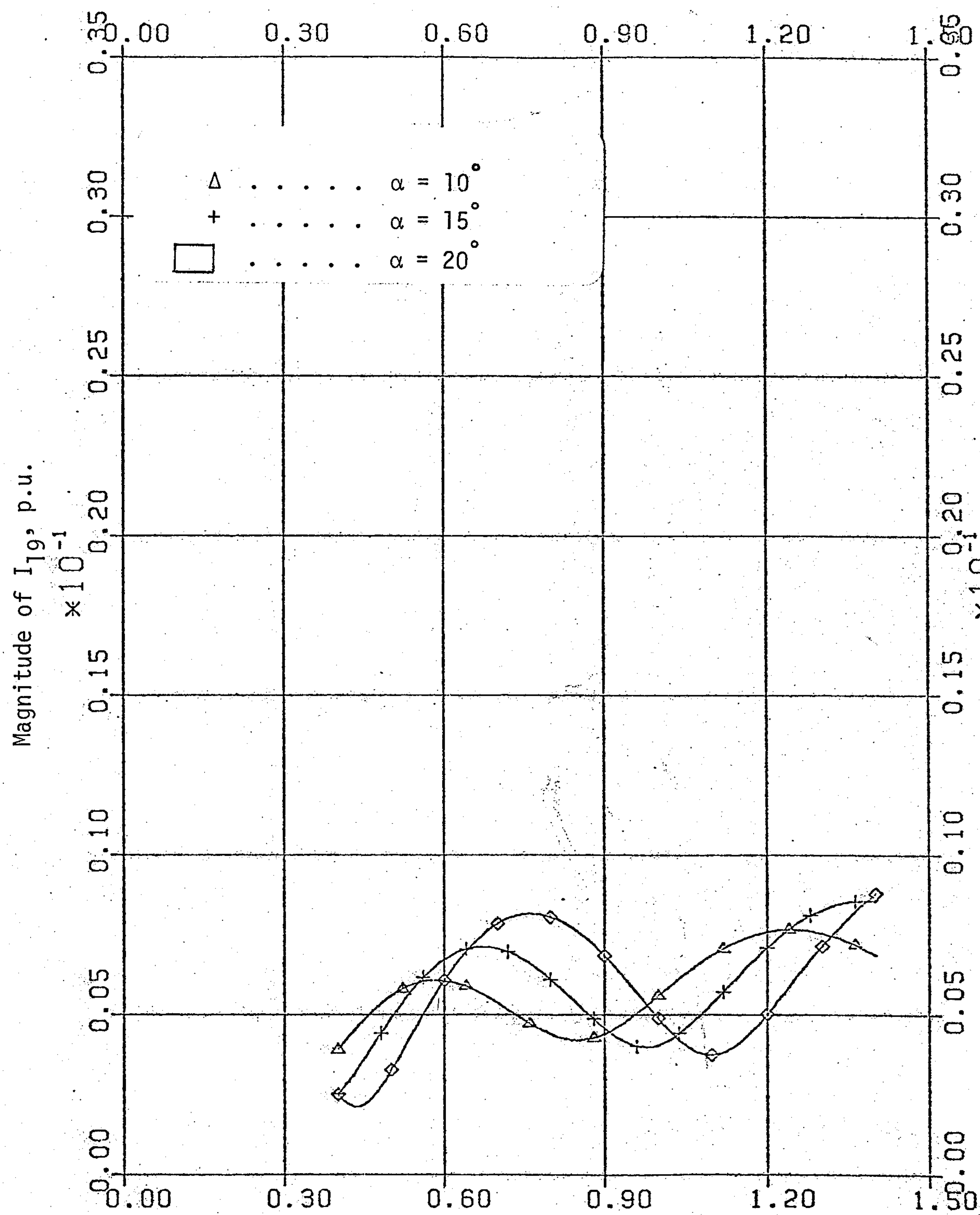
Direct Current, I_{dc} in p.u.

Fig. 2.6 Magnitude of 13th harmonic current as a function of I_{dc} in SB connection.



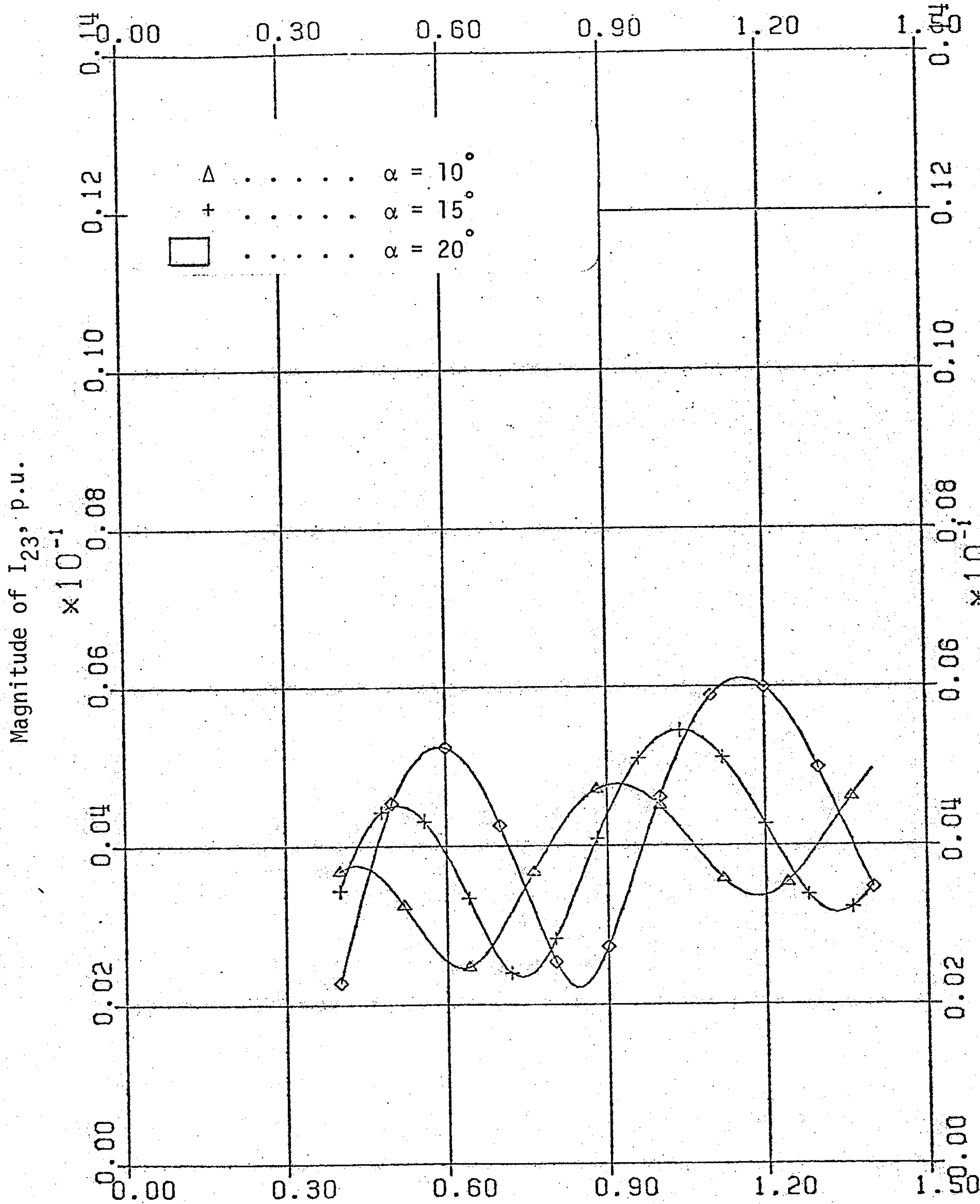
Direct Current, I_{dc} in p.u.

Fit. 2.7 Magnitude of 17th harmonic current as a function of I_{dc} in SB connection.



Direct Current, I_{dc} in p.u.

Fig. 2.8 Magnitude of 19th harmonic current as a function of I_{dc} in SB connection.



Direct Current, I_{dc} in p.u.

Fig. 2.9 Magnitude of 23rd harmonic current as a function of I_{dc} in SB connection.

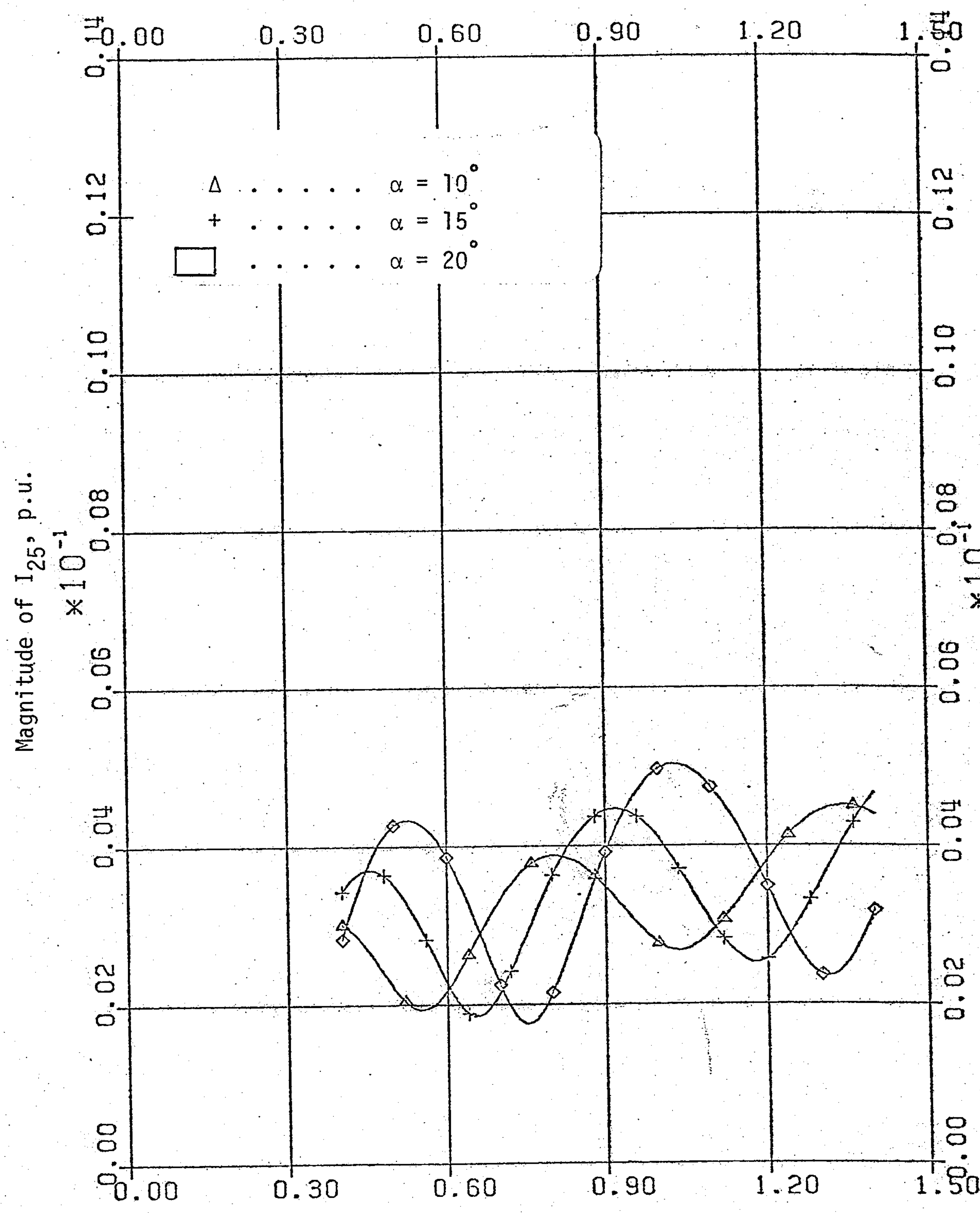


Fig. 2.10 Magnitude of 25th harmonic current as a function of I_{dc} in SB connection.

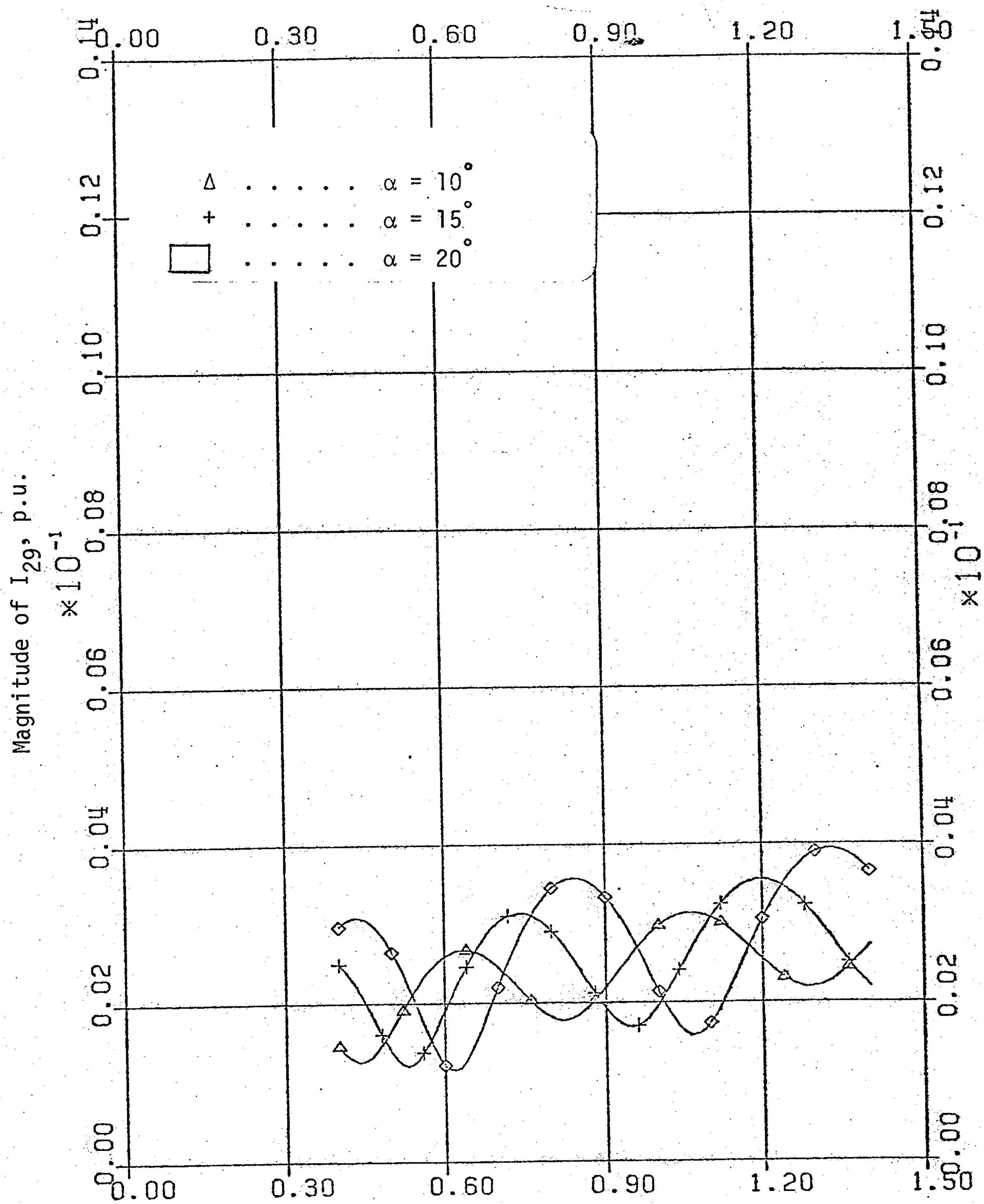
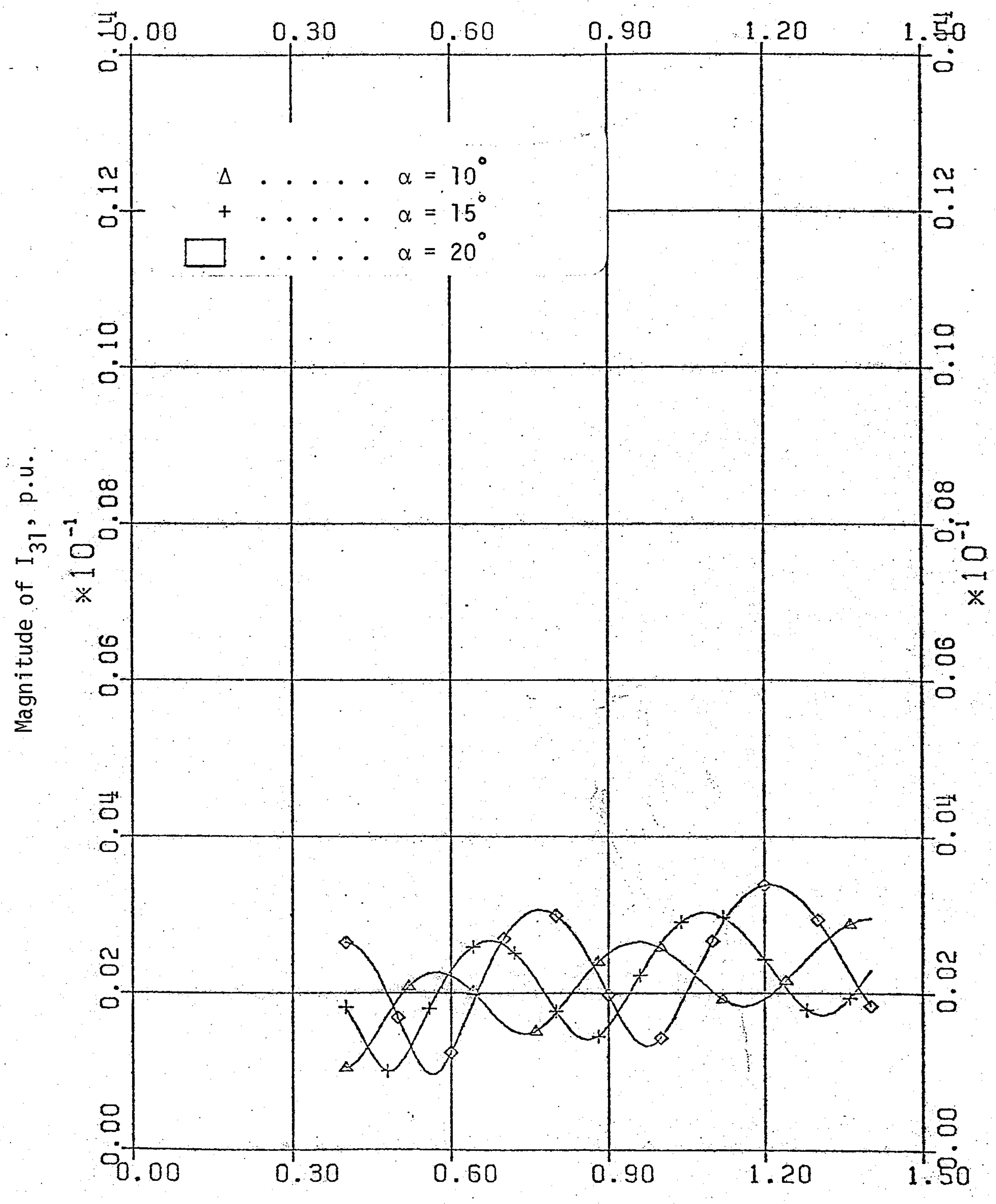
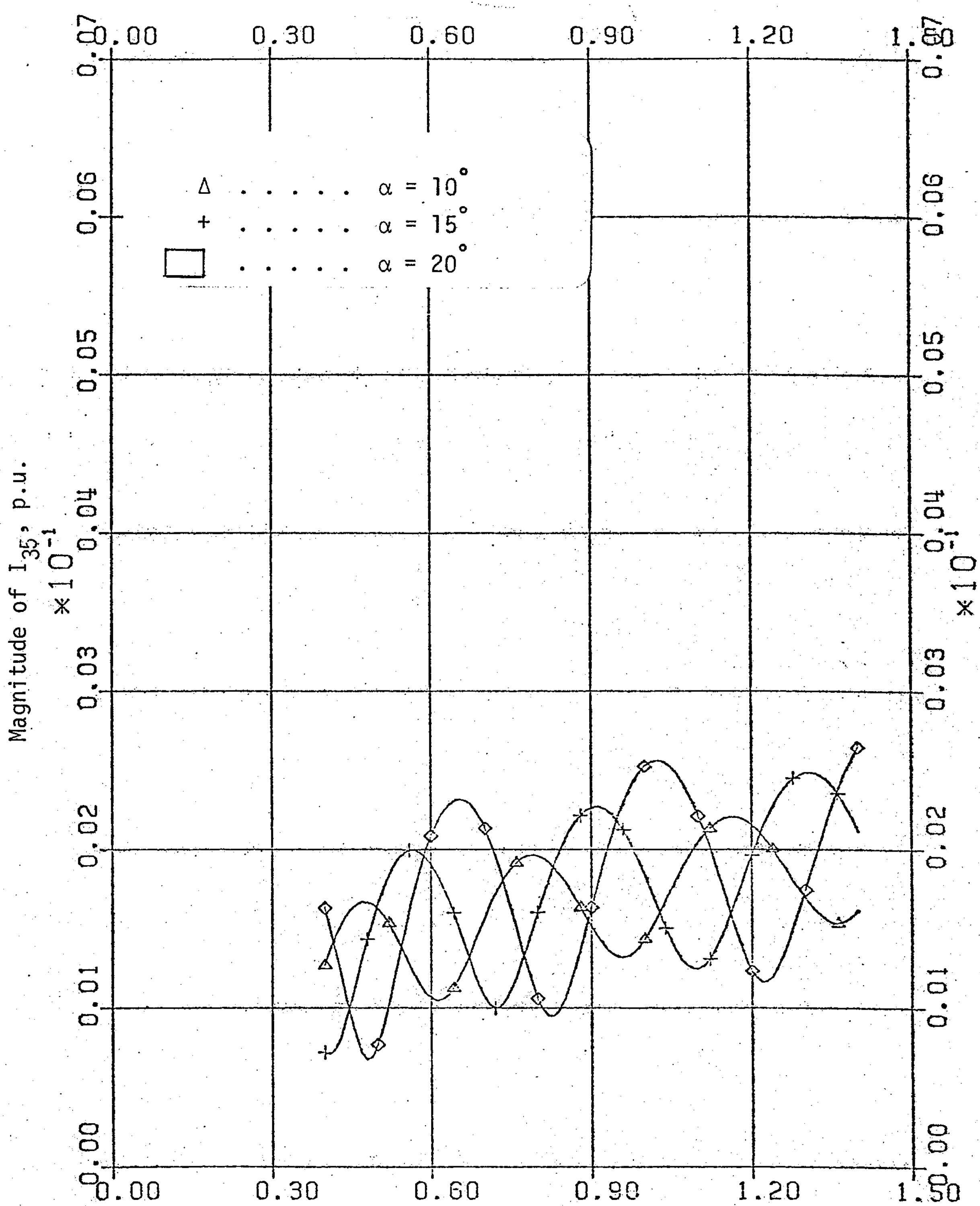


Fig. 2.11 Magnitude of 29th harmonic current as a function of I_{dc} in SB connection.



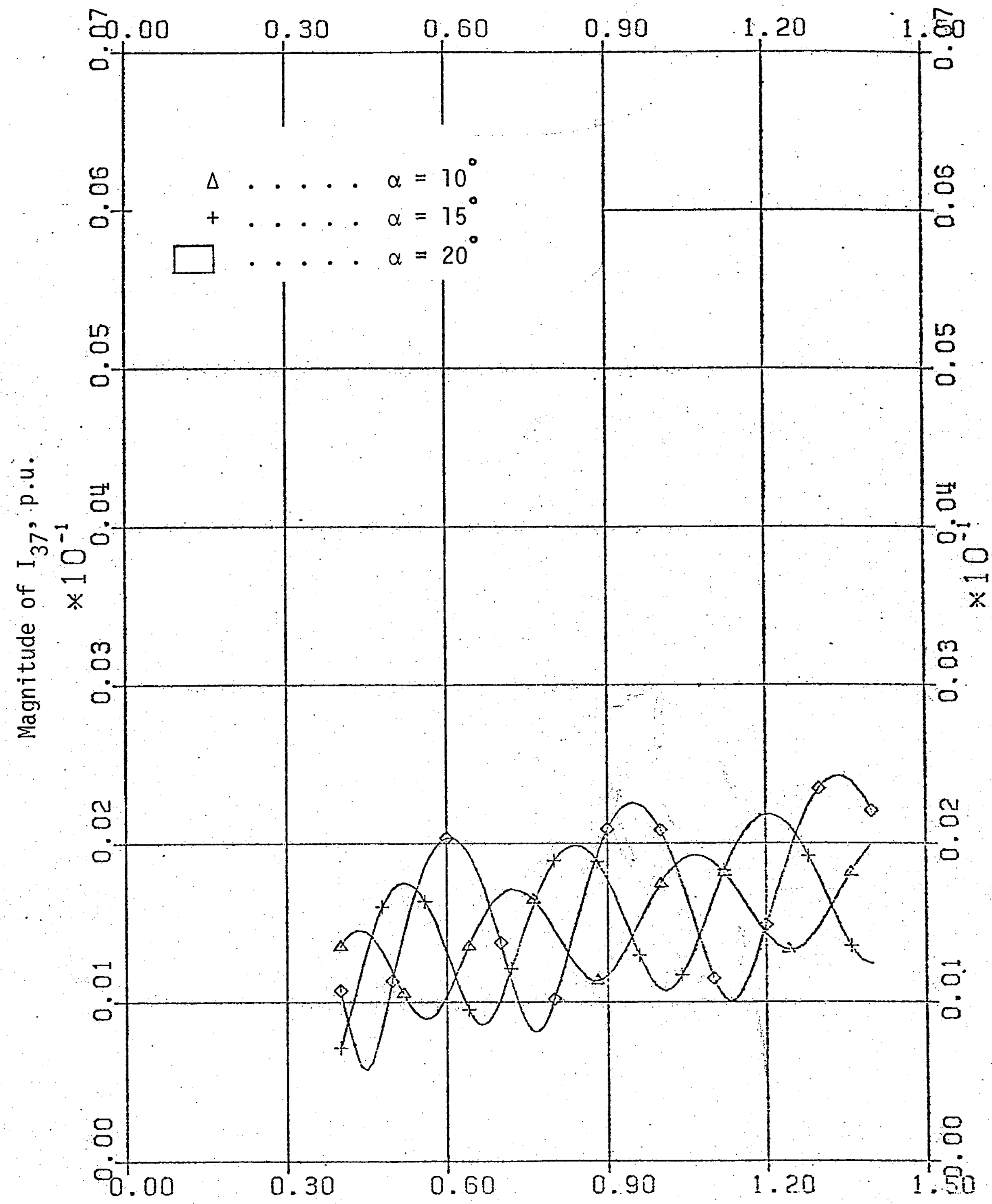
Direct Current, I_{dc} in p.u.

Fig. 2.12 Magnitude of 31st harmonic current as a function of I_{dc} in SB connection.



Direct Current, I_{dc} in p.u.

Fig. 2.13 Magnitude of 35th harmonic current as a function of I_{dc} in SB connection.



Direct Current, I_{dc} in p.u.

Fig. 2.14 Magnitude of 37th harmonic current as a function of I_{dc} in SB connection.

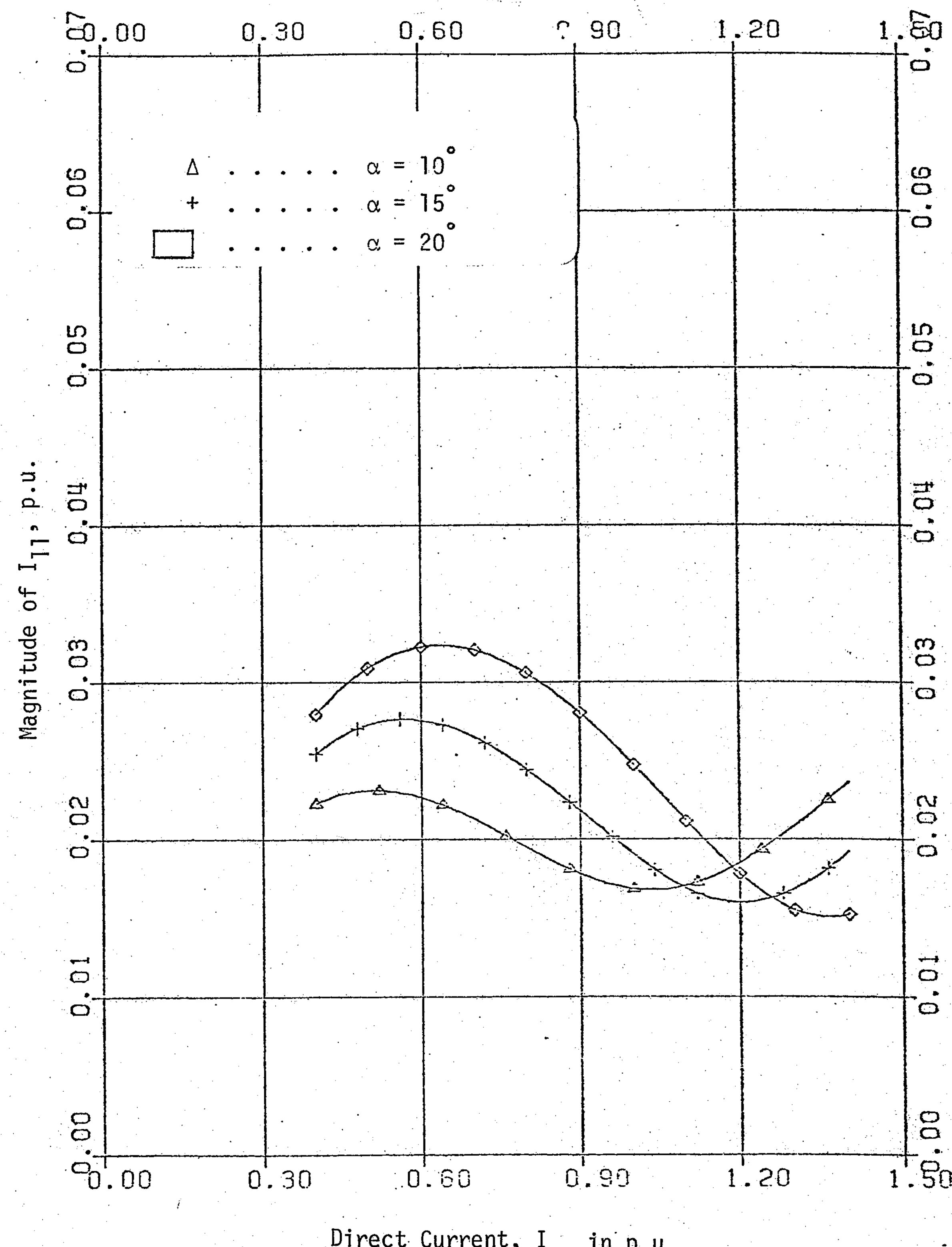
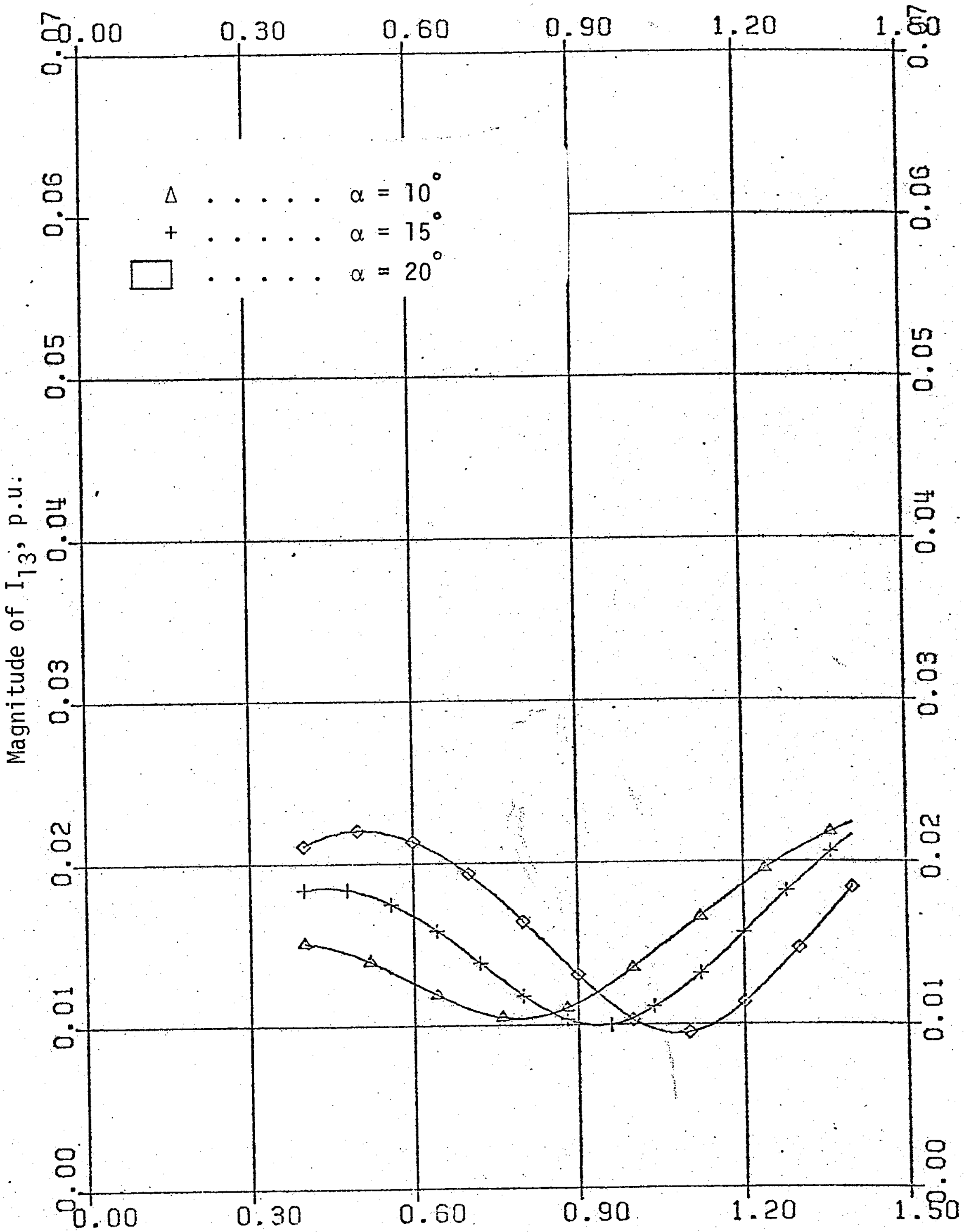
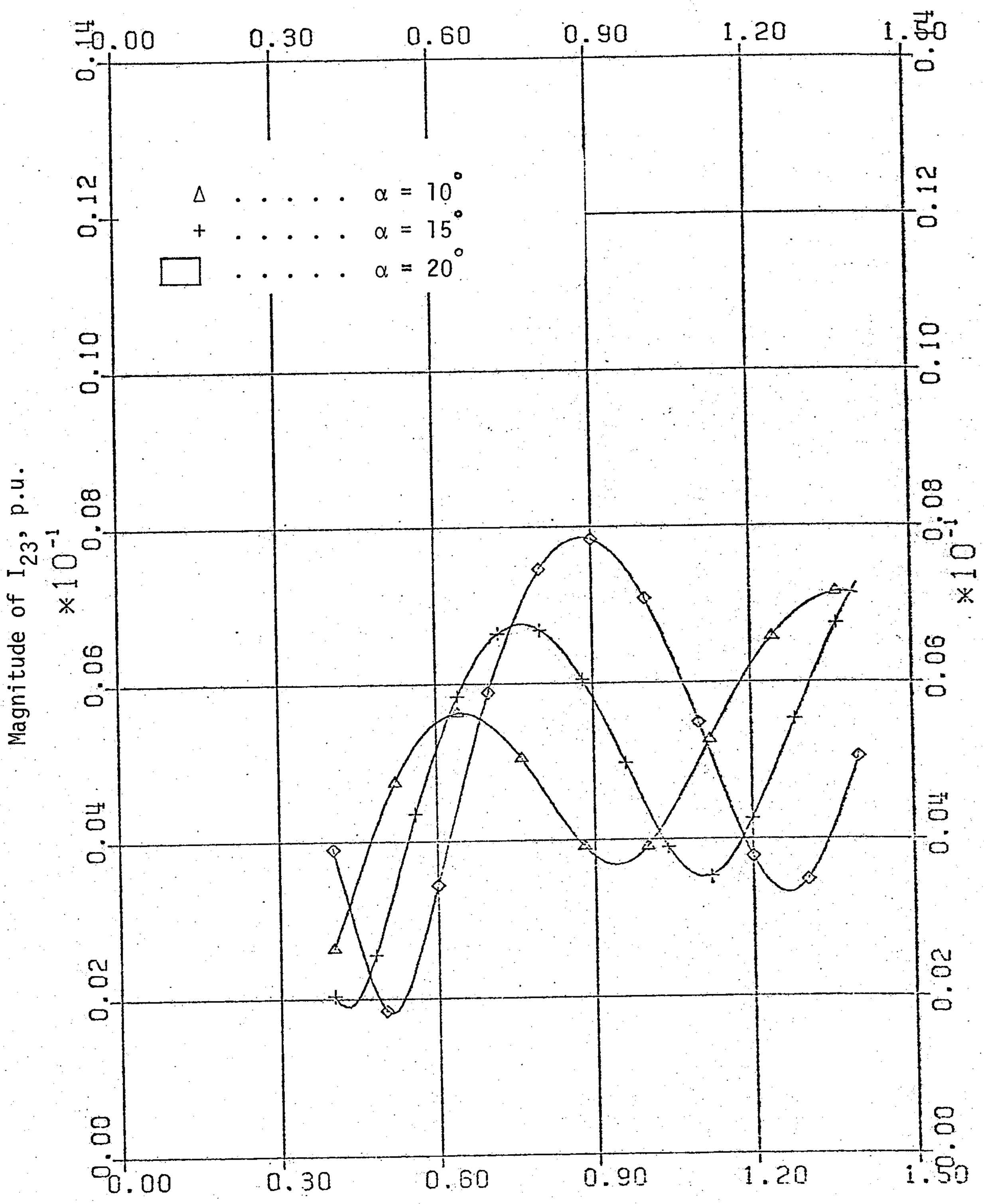


Fig. 2.15 Magnitude of 11th harmonic current as a function of I_{dc} in DB connection.



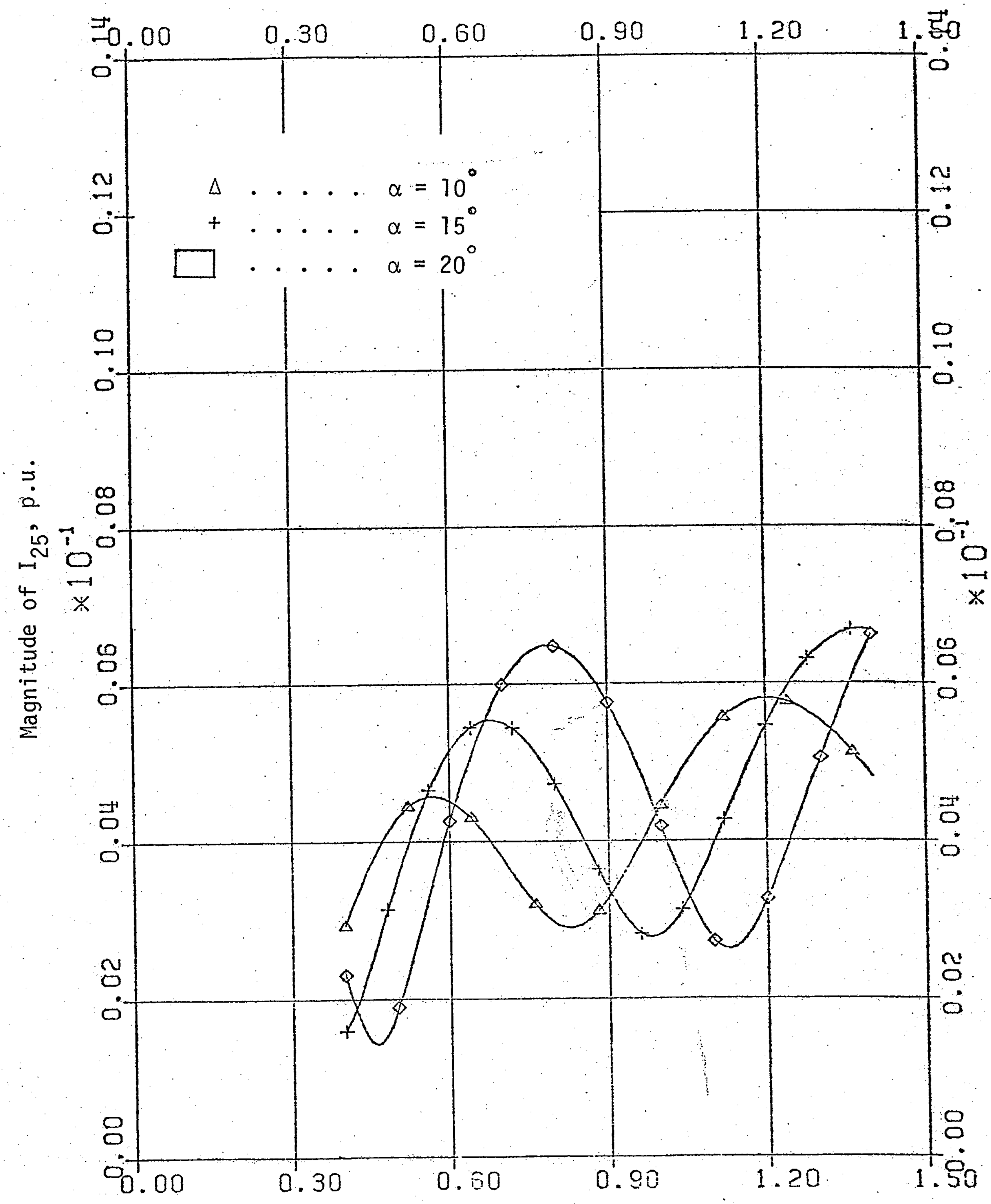
Direct Current, I_{dc} in p.u.

Fig. 2.16 Magnitude of 13th harmonic current as a function of I_{dc} in DB connection.



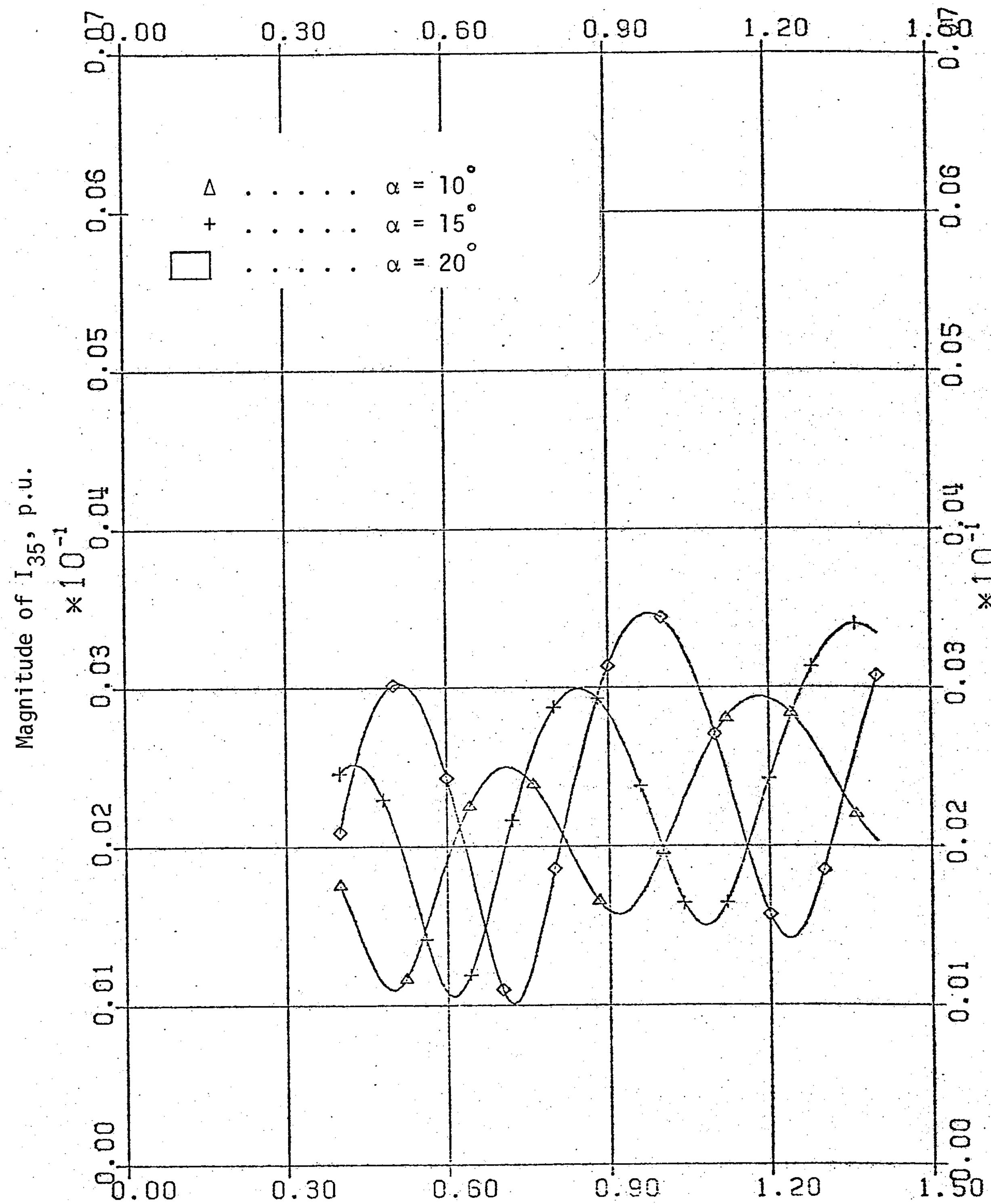
Direct Current, I_{dc} in p.u.

Fig. 2.17 Magnitude of 23rd harmonic current as a function of I_{dc} in DB connection.



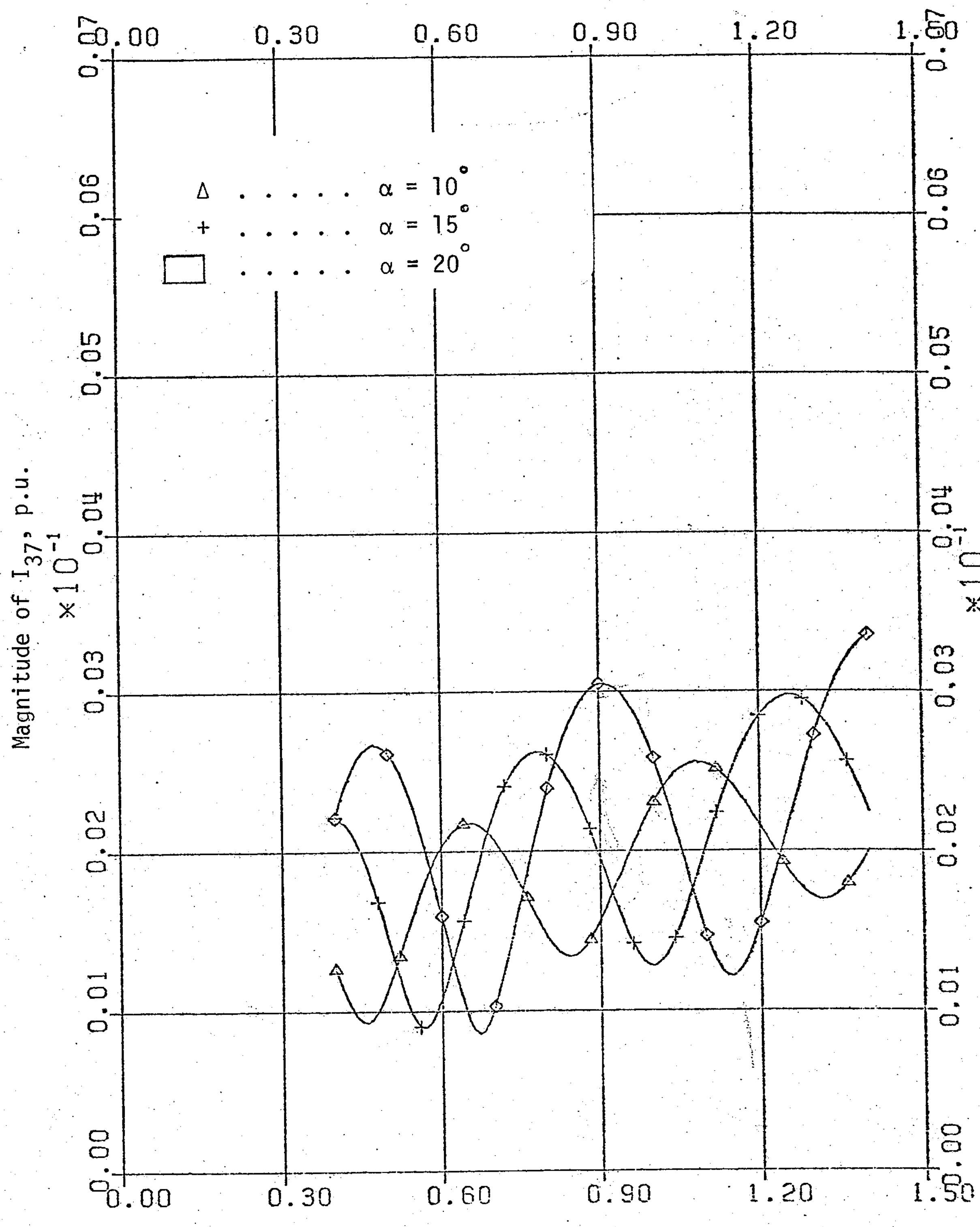
Direct Current, I_{dc} in p.u.

Fig. 2.18 Magnitude of 25th harmonic current as a function of I_{dc} in DB connection.



Direct Current, I_{dc} in p.u.

Fig. 2.19 Magnitude of 35th harmonic current as a function of I_{dc} in DB connection.



Direct Current, I_{dc} in p.u.

Fig. 2.20 Magnitude of 37th harmonic current as a function of I_{dc} in DB connection.

CHAPTER 3

ROTOR LOSSES

3.1 General

It has been shown in the previous chapter that the converter operation gives rise to harmonic currents of the order of $h = pn \pm 1$ in the a.c. lines. In unit schemes, since filters are not provided, these harmonic currents must flow through the generators. In the absence of harmonic currents in the stator phases and when the machine runs at synchronous speed, the rotor damper windings carry no current. The circulation of the harmonic currents of $pn \pm 1$ order in the stator give rise to currents of pn harmonic order in rotor electrical circuits. These therefore cause additional heating loss which must be evaluated accurately to determine the extent to which a given machine can be loaded without exceeding the rated temperature rise.

In addition to the I^2R losses in the rotor circuits, there would be additional iron and stray load losses in the machine. It is very difficult to estimeate the iron losses accurately, particularly under variable load operating conditions and since there is no published data available on this aspect of the machine performance, at best only an educated guess can be made. The details of calculation lie clearly outside the scope of this thesis, hence, no attempt for the calcualtion of iron losses is made.

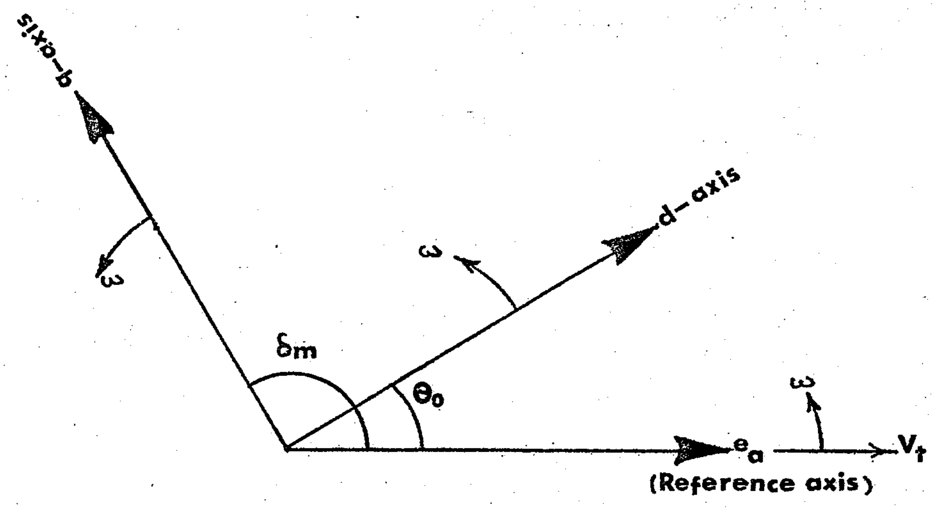


Fig 3·1 Position of rotor d-axis at t=0

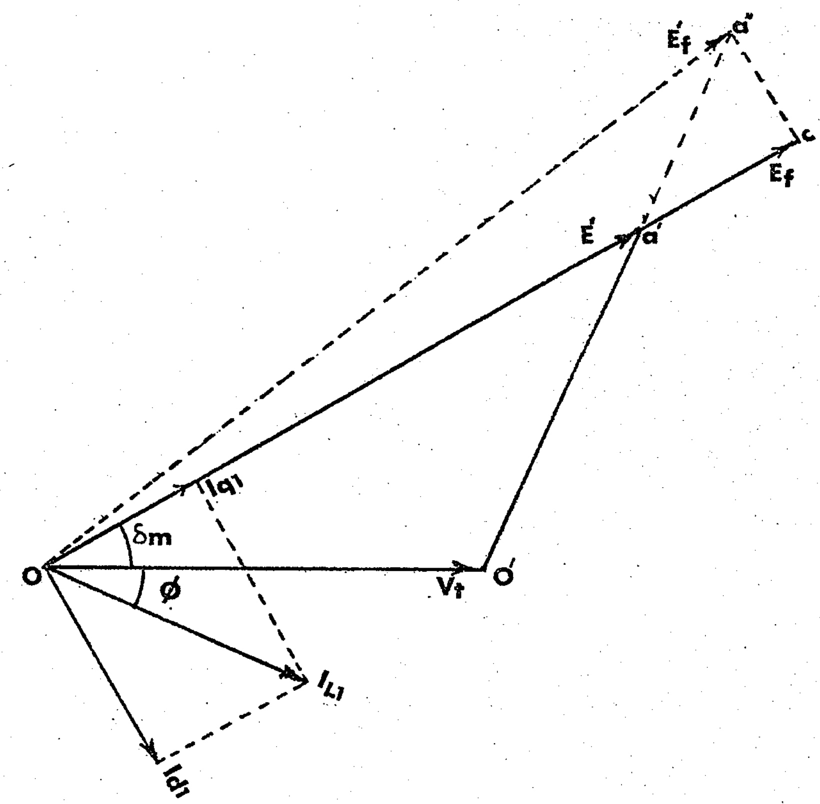


Fig 3.2 (a) **Steady state phasor diagram of a synchronous generator**

3.2 Current Harmonics in the Transformed Model of Generators

To find the effects of these harmonics on the rotor circuits of the synchronous generator connected to the converter, the d - q axis model of the generator is used. By d - q - o transformation[10] these harmonic currents in phases a, b and c are resolved into d - q - o current components.

d - q transformation in p.u. is

$$\begin{vmatrix} i_{hd} \\ i_{hq} \\ i_{h0} \end{vmatrix} = 2/3 \begin{vmatrix} \cos\theta & \cos(\theta-2\pi/3) & \cos(\theta+2\pi/3) \\ -\sin\theta & -\sin(\theta-2\pi/3) & -\sin(\theta+2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{vmatrix} \begin{vmatrix} i_{ah} \\ i_{bh} \\ i_{ch} \end{vmatrix} \qquad (3.1)$$

where $\theta = \theta_0 + \omega t$ (3.2)

Where θ_0 defines the position of rotor d-axis with reference to the axis of phase a at time t = 0, as shown in Fig. 3.1

Let θ' = Angle of q-axis with phase a-axis

$= \theta + \pi/2$

$= \theta_0 + \omega t + \pi/2$ (3.3)

From synchronous machine theory

$$\theta' = \omega t + \delta_m$$

where δ_m = Angle between q-axis and a rotating reference frame (usually voltage of phase a)

= Load angle of the machine

$= \theta_0 + \pi/2$

In terms of δ_m

$$\theta = \omega t + \delta_m - \pi/2 \tag{3.4}$$

The load angle δ_m can be found from the steady state phasor diagram[8] of the generator shown in Fig. 3.2.(a).

For the converter

$$\cos\phi = \frac{1}{2}(\cos\alpha + \cos\delta) \tag{3.5}$$

From the phasor diagram in Fig. 3.2 (a)

$$I_{L1}(\text{complex r.m.s.}) = I_{L1}(\cos\phi - j\sin\phi)$$

$$E' = v_t + j\, I_{L1}\, x_q \tag{3.6}$$

where $\quad v_t =$ Terminal voltage of the generator

The phase angle of E' with respect to terminal voltage v_t (reference) gives generator load angle δ_m.

The instantaneous values of the harmonic currents in phases a, b and c is represented by cosine function as follows:

$$i_{ah} = \sqrt{2}\, I_h \cos(h\omega t - \phi_h)$$

$$i_{bh} = \sqrt{2}\, I_h \cos[h(\omega t - 2\pi/3) - \phi_h]$$

$$i_{ch} = \sqrt{2}\, I_h \cos[h(\omega t + 2\pi/3) - \phi_h] \tag{3.7}$$

Using d - q - o transformation, d - q - o current components are

$$\begin{vmatrix} i_{dh} \\ i_{qh} \\ i_{0h} \end{vmatrix} = \frac{2}{3} \begin{vmatrix} \cos(\omega t+\delta_m-\pi/2) & \cos(\omega t+\delta_m-\pi/2-2\pi/3) & \cos(\omega t+\delta_m-\pi/2+2\pi/3) \\ \cos(\omega t+\delta_m) & \cos(\omega t+\delta_m-2\pi/3) & \cos(\omega t+\delta_m+2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{vmatrix} \cdot$$

$$\begin{vmatrix} I_h \cos(h\omega t-\phi_h) \\ I_h \cos[h(\omega t-2\pi/3)-\phi_h] \\ I_h \cos[h(\omega t+2\pi/3)-\phi_h] \end{vmatrix} \tag{3.8}$$

The magnitudes of i_{dh} and i_{qh} from eqn. 3.8 will be r.m.s. values

for $h = pn - 1$

$$i_{dh} = I_h \cos[(h + 1)\ \omega t - \phi_h + \delta_m - \pi/2]$$

$$= I_h \sin[(h + 1)\ \omega t - \phi_h + \delta_m] \tag{3.9}$$

$$i_{qh} = I_h \cos[(h + 1)\ \omega t - \phi_h + \delta_m] \tag{3.10}$$

for $h = pn + 1$

$$i_{dh} = I_h \cos[(h - 1)\ \omega t - \phi_h - \delta_m + \pi/2]$$

$$= -I_h \sin[(h - 1)\ \omega t - \phi_h - \delta_m] \tag{3.11}$$

$$i_{qh} = I_h \cos[(h - 1)\ \omega t - \phi_h - \delta_m] \tag{3.12}$$

The d - q components of the fundamental a.c. current are

$$i_{d1} = I_{L1} \sin(\delta_m + \phi_1) \quad (3.13)$$

$$i_{q1} = I_{L1} \cos(\delta_m + \phi_1) \quad (3.14)$$

All the currents i_{dh} and i_{qh} are of $pn\omega$ frequency, i.e. the harmonics $h = pn \pm 1$ in the stator windings when transformed into d - q components turn out to be the currents of $pn\omega$ frequency. As the stator and rotor are inductively coupled, the harmonic currents of $pn\omega$ frequency will be induced in the rotor circuits. The harmonic currents of $pn\omega$ frequency due to $h = pn - 1$ and $h = pn + 1$ should be added vectorially because these are of the same frequency.

$$i_{dpn} = -I_{pn+1} \underline{/-\delta_m - \phi_h} + I_{pn-1} \underline{/\delta_m - \phi_h} \quad (3.15)$$

$$i_{qpn} = I_{pn+1} \underline{/-(\phi_h + \delta_m)} + I_{pn-1} \underline{/-\phi_h + \delta_m} \quad (3.16)$$

3.3 Detailed Transformed Model of the Generators

In section 3.2 the harmonic currents injected into the stator windings of the generator are transformed to d - q - o components. The currents induced in the rotor circuits can be calculated by considering the synchronous generator as a multiwinding transformer with given current in its primary winding.

For a synchronous generator with k number of damper circuits on each axis, the per-unit voltage equations for field and damper circuits are as follows[9]:

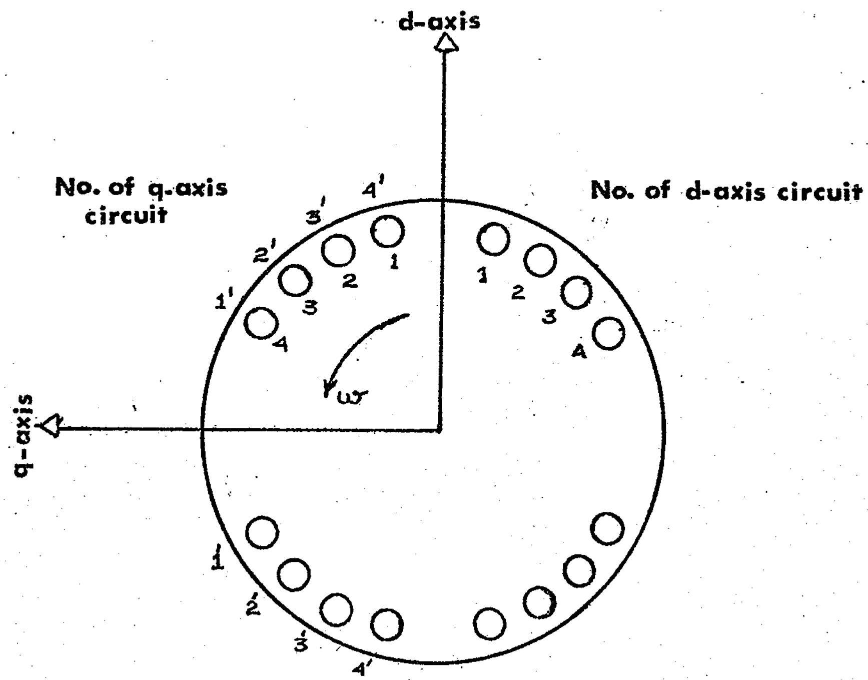


Fig 3·2 (b) Arrangement of nested damper circuit on d- and q-axis

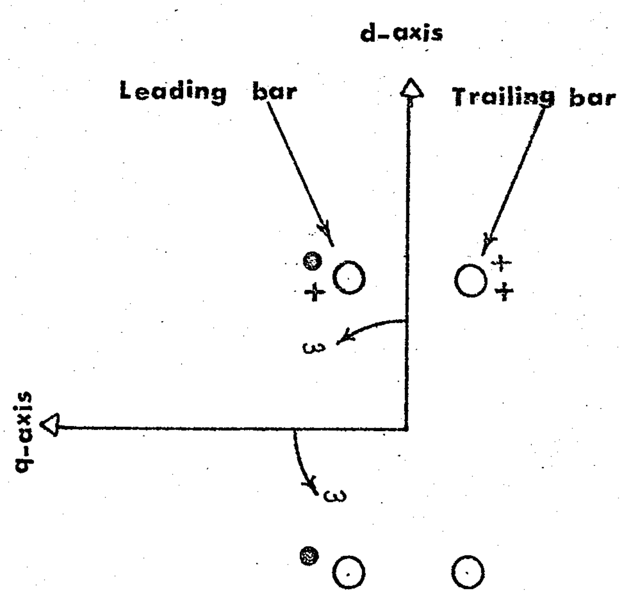


Fig 3·2 (c) Current in the bars of nested circuits

Direct axis

$$\begin{vmatrix} jsx_{dfd} & r_{ff} + jsx_{ff} & jsx_{1fd} & - & jsx_{kfd} \\ jsx_{d1d} & jsx_{f1d} & r_{11d} + jsx_{11d} & - & jsx_{k1d} \\ - & - & - & - & - \\ jsx_{dkd} & jsx_{fkd} & jsx_{1kd} & - & r_{kkd} + jsx_{kkd} \end{vmatrix} \cdot \begin{vmatrix} I_{ds} \\ I_{fs} \\ I_{1ds} \\ - \\ - \\ I_{kds} \end{vmatrix} = \begin{vmatrix} \\ 0 \\ 0 \\ - \\ - \\ 0 \end{vmatrix} \qquad (3.17)$$

Similarly for quadrature-axis

$$\begin{vmatrix} jsx_{q1q} & r_{11q}+jsx_{11q} & - & - & jsx_{k1q} \\ - & - & - & - & - \\ - & - & - & - & - \\ jsx_{qkq} & jsx_{11kq} & - & - & r_{kkq}+jsx_{kkq} \end{vmatrix} \cdot \begin{vmatrix} I_{qs} \\ I_{1qs} \\ - \\ - \\ I_{kqs} \end{vmatrix} = \begin{vmatrix} \\ 0 \\ - \\ - \\ 0 \end{vmatrix} \qquad (3.18)$$

In equations 3.17 and 3.18 s denotes the slip which is equal to pn. The base quantities for the stator windings are the rated phase voltage and rated phase current. For normalization of circuit parameters x_{ad} base[10] is chosen.

With the x_{ad} base, the base current in any rotor circuit is taken to be that current which induces in each phase a direct-axis voltage $\sqrt{2}\, x_{ad}\, I_p$ on no load. x_{ad} is the armature reactance in ohms/phase and I_p

is the rated r.m.s. current. The same base can be used for the quadrature axis rotor circuit.

The chosen x_{ad} base makes

$$x_{ad} = x_{dfd} = x_{kfd} = x_{fkd} = x_{lkd} = x_{kld} \tag{3.19}$$

and

$$x_{aq} = x_{qkq} = x_{klq} = x_{lkq} \tag{3.20}$$

Equations 3.17 and 3.18 may be rewritten as

$$\begin{vmatrix} x_{ad} & \frac{r_{ff}}{jpn} + x_{ff} & x_{lfd} & - & x_{kfd} \\ x_{dld} & x_{fld} & \frac{r_{lld}}{jpn} + x_{lld} & - & x_{kld} \\ - & - & - & - & - \\ x_{dkd} & x_{fkd} & x_{lkd} & - & \frac{r_{kkd}}{jpn} + x_{kkd} \end{vmatrix} \cdot \begin{vmatrix} I_{dpn} \\ I_{fpn} \\ I_{ldpn} \\ - \\ I_{kdpn} \end{vmatrix} = 0 \tag{3.21}$$

$$\begin{vmatrix} x_{aq} & \frac{r_{11q}}{jpn} + x_{11q} & - & - & x_{k1q} \\ - & - & - & - & - \\ x_{qkq} & x_{1kq} & - & - & \frac{r_{kkq}}{jpn} + x_{kkq} \end{vmatrix}$$

$$\begin{vmatrix} I_{qpn} \\ I_{1qpn} \\ - \\ I_{kqpn} \end{vmatrix} = 0 \tag{3.22}$$

In equations 3.21 and 3.22, I_{dpn} and I_{qpn} are known (Eqn. 3.15 and 3.16). When all elements of the impedance matrix in equations 3.21 and 3.22 are known, the harmonic currents in the rotor circuits are calculated. In the above equations the d.c. voltage source in the field circuit is assumed to be of zero impedance. If, however, a finite value of this impedance be known it can be lumped with $r_{ff} + jx_{ff}$ without any loss of generality.

Should the actual current in the damper bars be required, it is calculated by using equations 3.23 and 3.24.

Figs. 3.2 (a) and (b) shown the arrangement and current flow in the damper bars.

For leading bar $I_b = I_{kdpn} - I_{(k-m)qpn}$ (3.23)

For lagging bar $I_b = I_{kdpn} + I_{(k+m)qpn}$ (3.24) where I_b = Actual current in the bar

m = Number of circuit on d-axis which the bar under consideration forms

k = Total number of nested circuits (on each axix same number)

The above analysis may be used for an accurate calculation of rotor I^2R losses. However, usually only designers of machines have access to all values of the impedance parameters of rotor circuits. In the absence of this data a simpler model of one damper circuit on each axis is used.

Glebov[7] has also done a similar type of work but adopting a different approach. According to author's knowledge, Glebov is the only one who has done such type of work but his method of calculations is somewhat obscure.

3.4 A Simpler Transformed Model of the Generator

Such a model has one damper circuit on each axis. Fig. 3.3 (a) shows the physical model, while Fig. 3.3 (b) and (c) show the equivalent circuits. For the model in question, the equations 3.21 and 3.22 simplfy to

For direct-axis

$$\begin{vmatrix} x_{ad} & \frac{r_{ff}}{jpn} + x_{ff} & x_{1fd} \\ x_{d1d} & x_{f1d} & \frac{r_{11d}}{jpn}\, x_{11d} \end{vmatrix} \begin{vmatrix} I_{dpn} \\ I_{fpn} \\ I_{1dpn} \end{vmatrix} = 0 \qquad (3.25)$$

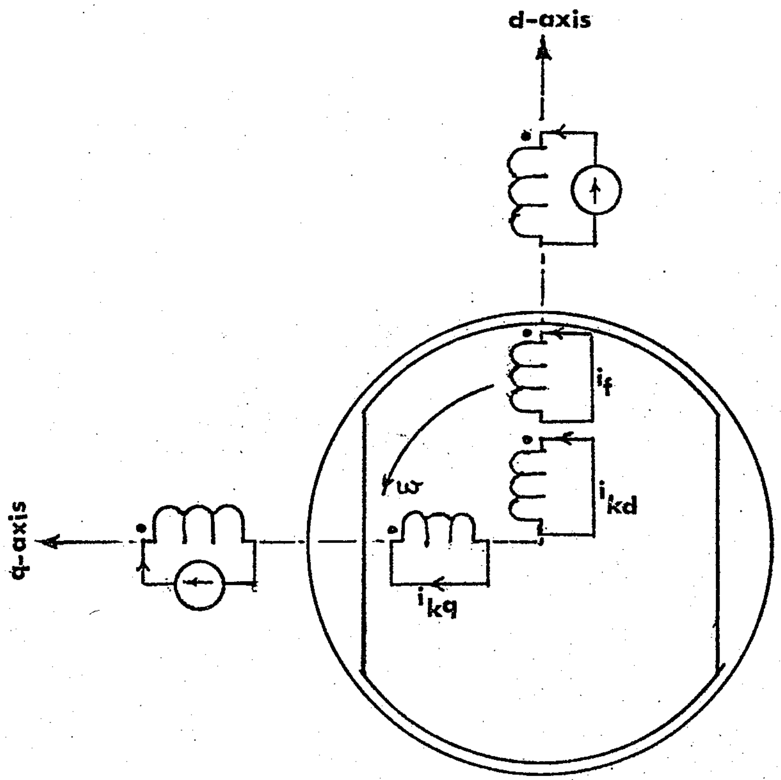


Fig 3.3 (a) d-q axis model

Similarly for quadrature axis

$$\begin{vmatrix} x_{aq} & \frac{r_{11q}}{jpn} + x_{11q} \end{vmatrix} \begin{vmatrix} I_{qpn} \\ I_{1qpn} \end{vmatrix} = 0 \qquad (3.26)$$

The circuit parameters of the impedance matrix in equation 3.25 and 3.26 are calculated from the given designer's data as shown in Appendix B.

I_{dpn} and I_{qpn} are calcualted from equations 3.15 and 3.16, the currents I_{fpn}, I_{1dpn} and I_{1qpn} can be determined. I_{fpn}, I_{1dpn} and I_{1qpn} are the r.m.s. values of currents of $pn\omega$ frequency induced in the field, damper circuit on d-axis and damper circuit on q-axis respectively, due to the harmonic currents $pn \pm 1$ in the stator circuits. The stator and rotor losses may be obtained from the following expressions.

$$\text{Stator Losses} = \sum \left(|I_{dpn}|^2 \cdot r_d + |I_{qpn}|^2 \cdot r_q \right) \qquad (3.27)$$

$$\text{Rotor Losses} = \sum \left(|I_{fpn}|^2 \, r_{ff} + |I_{1dpn}|^2 \cdot r_{11d} + \left(|I_{1qpn}|^2 \cdot r_{11q} \right) \right) \qquad (3.28)$$

In the above expressions, resistances used are the effective resistances to account for the skin effect. These resistances are function of frequency as summarized below:

(1) $R' = \psi(f)$
where R' is the resistance and f is the frequency.

(2) Same relationship should not be used for all machines since the frequency dependance of resistance depends upon the configuration of the rotor conductors [Babb and Williams[11]].

(3) Best approximation in the absence of data is:

$$R' = R\sqrt{pn} \quad \text{[Krishnayya[5], Fitzgerald[8]]}$$

where R' = Effective resistance at frequency pn.

R = Effective resistance at fundamental frequency.

The losses calculated in equations 3.27 and 3.28 are the additional losses in the generator if the harmonics are allowed to flow into the generator. Without these harmonics, losses in the stator will be due to the fundamental component of a.c. current and in the rotor due to steady-state d.c. field current as in equation 3.29 and 3.30:

$$\text{Stator Loss} = |I_{d1}|^2 \cdot r_d + |I_{q1}|^2 \cdot r_q \qquad (3.29)$$

$$\text{Rotor Loss} = |I_f|^2 \cdot r_{ff} \qquad (3.30)$$

Glebov[7] has given some expressions for the calculation of rotor losses for the same type of generator model as has been used here. In his work, assumption has been made that harmonic components of the stator currents of the order of pn + 1 and pn - 1 create m.m.f.'s, which pulsate with respect to the rotor along the axis forming an angle $\pi/4$ with the direct or quadrature axes. This assumption is not justified because it depends upon the magnitude and phase angle of these harmonic components.

It is very difficult to make use of his results for comparative evaluation for the simple reason that he neither gives the parameter values of the machines nor the particulars of the converter operation, e.g. α, u, x_c, etc. This in effect justified partially the need to take up the investigation as described in this chapter.

3.5 Rotor Losses (SB and DB Connection)

These type of connections have been discussed in detail, in chapter 1, as shown in Figs. 1.3 and 1.4 respectively. Harmonics of the following characteristic order appear in SB and DB connections.

$h = 5, 7, 11, 13, \ldots\ldots$ (SB connection, 6-pulse operation)

and $h = 11, 13, 23, 24, \ldots\ldots$ (DB connection, 12-pulse operation)

The rotor losses can be calculated by using equations 3.27 and 3.28. A computer program has been written, as shown in Appendix C, which calculates the magnitude and phase angle of these harmonics and the rotor losses.

The rotor losses for these connections have been examined for the following operating conditions:

(1) $\alpha = 10^\circ, 15^\circ, 20^\circ$

(2) $I_{dc} = 0.4$ p.u. to 1.4 p.u.

(3) $x_t = 0.12$

(4) $x''_d = 0.2375$

The variation of the rotor losses with the change in I_{dc} are plotted for SB connection in Fig. 3.4 and for DB connection in Fig. 3.5, for different values of α. In all the above calculations, the secondary voltage and commutation reactance are kept constant. The change in I_{dc} is brought by varying the overlap angle u as shown in the following equation 3.31. The power on the d.c. as well as a.c. side of the converter

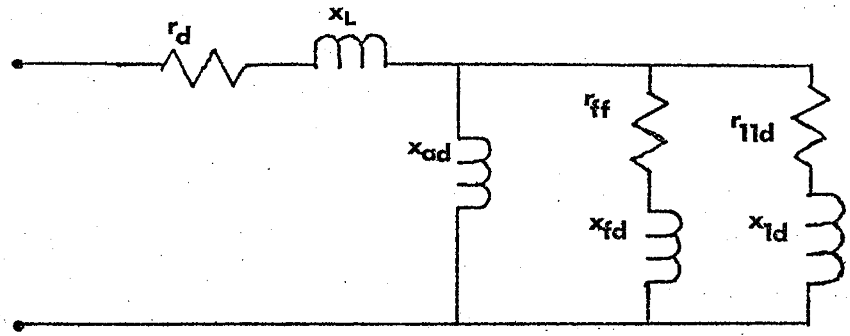


Fig 3·3(b) Equivalent circuit d-axis

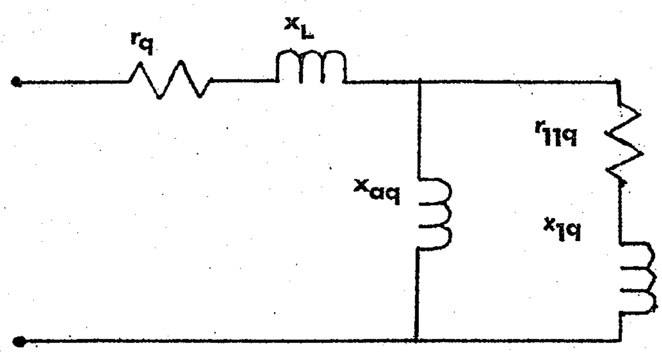


Fig 3·3(c) Equivalent circuit q-axis

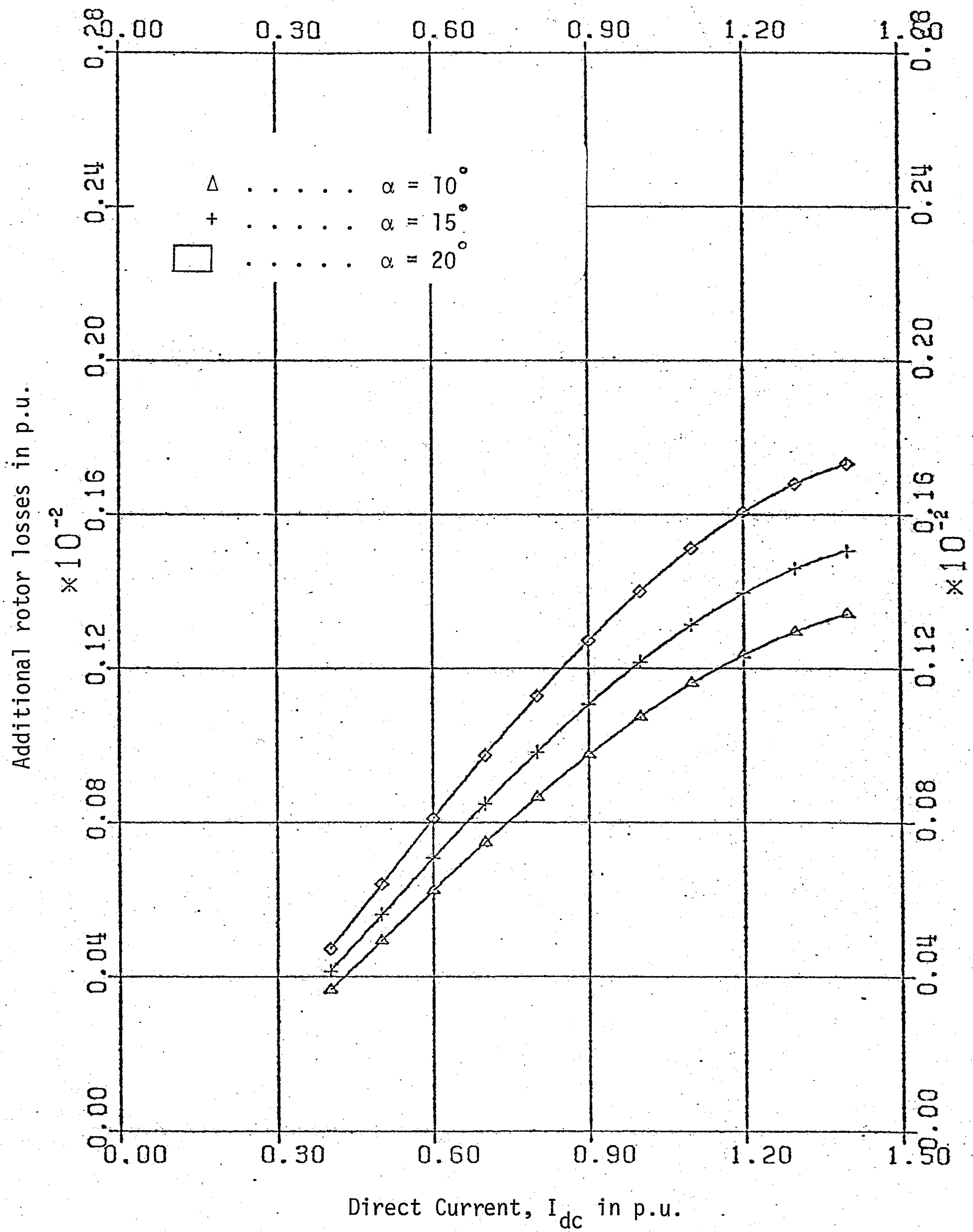
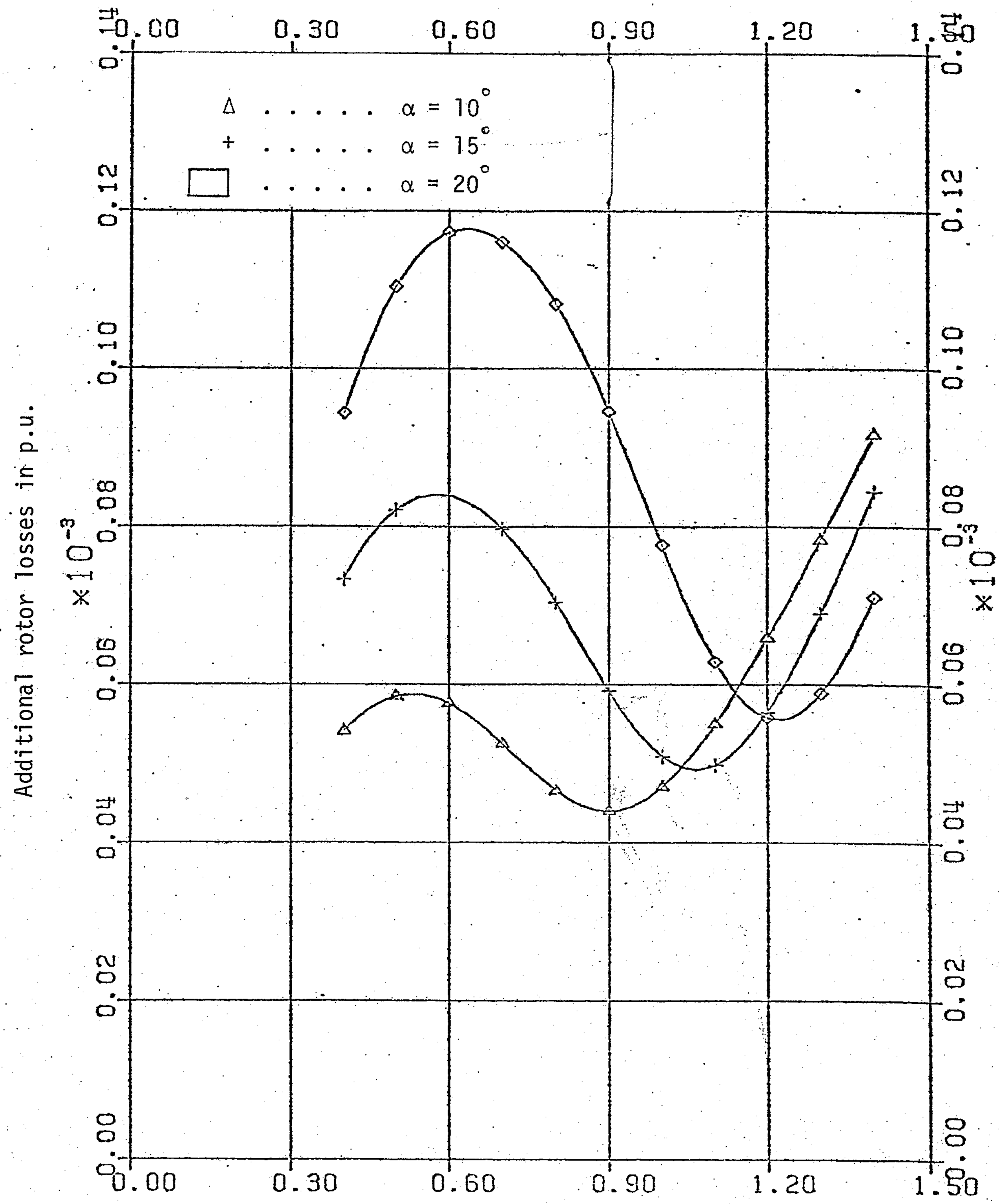
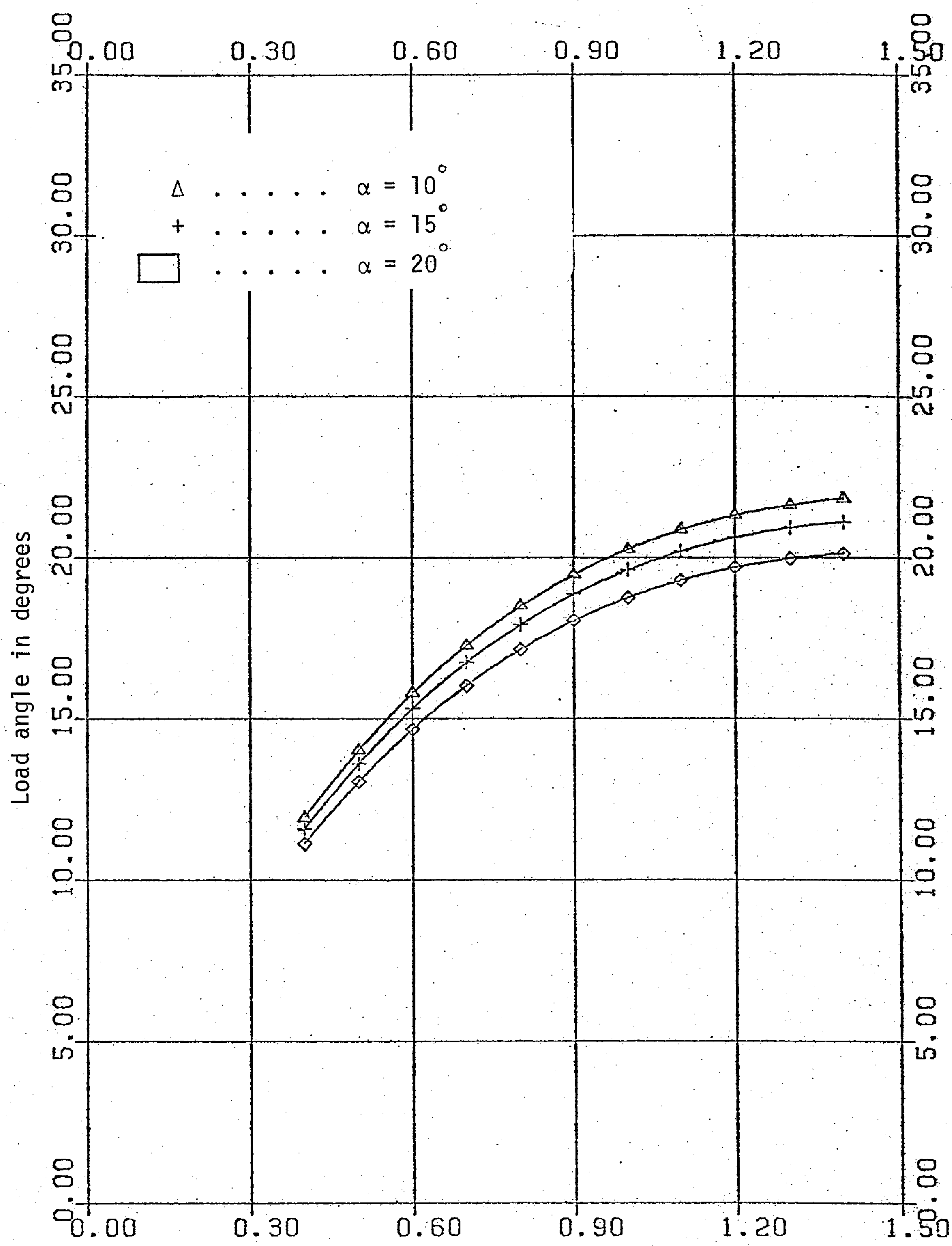


Fig. 3.4 Additional rotor losses of a generator as a function of I_{dc} in SB connection.



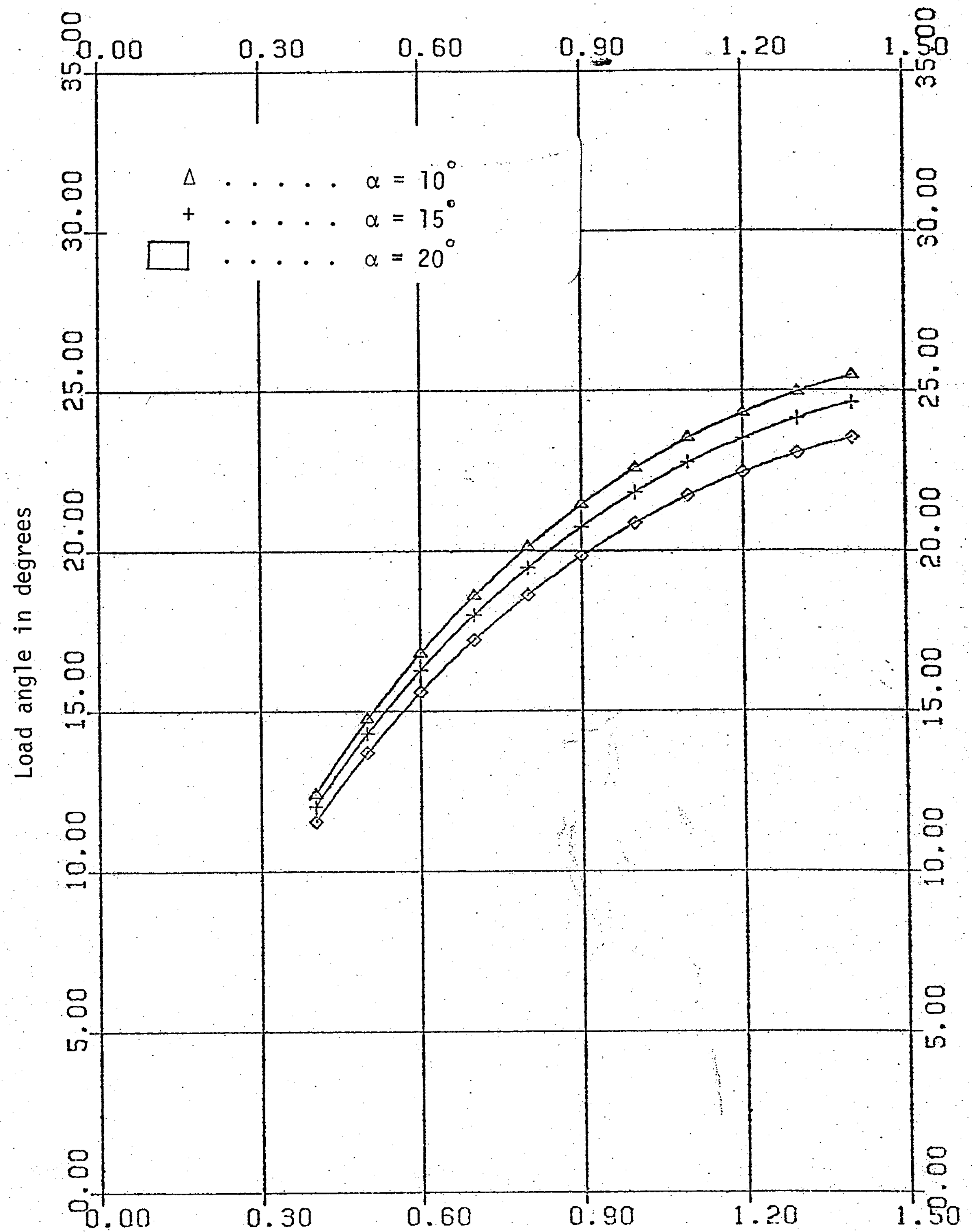
Direct Current, I_{dc} in p.u.

Fig. 3.5 Additional rotor losses of a generator as a function of I_{dc} in DB connection.



Direct Current, I_{dc} in p.u.

Fig. 3.6 Load angle of a generator as a function of I_{dc} in SB connection.



Direct Current, I_{dc} in p.u.

Fig. 3.7 Load angle of a generator as a function of I_{dc} in DB connection.

changes by changing I_{dc} as x_c has been kept constant.

$$I_{dc} = \frac{3}{\pi} \frac{E}{x_c} (\cos\alpha - \cos(\alpha + u)) \tag{3.31}$$

$$x_c = x_d'' + x_t \text{ (SB connection)} \tag{3.32}$$

$$x_c = x_d''/2 + x_t \text{ (DB connection)} \tag{3.33}$$

The results of Figs. 3.4 and 3.5 give an idea of the rotor losses of a particular system under certain operating conditions. The rotor losses in two types of unit connections are summarized below for one operating condition.

Type of Connection	Operating Specification α, I_{dc}	Additional Rotor Losses p.u.	Additional Total Losses p.u.
single-block	15°, 1.0 p.u.	.0012168	0.001589
double-block	15°, 1.0 p.u.	.0000498	0.000071

Similar losses also occur in a conventional scheme when the filters go off-tune or are taken out of service due to system fault and can be calculated by the method described above.

As is clear from Figs. 3.4 and 3.5, the rotor losses, in the case of SB connection, are enormously high as compared to DB connection. This is because of the presence of predominant 5th and 7th harmonics in SB connections. Figs. 3.6 and 3.7 show the variation in load angle of the machine for various values of I_{dc}.

If these losses are more than the permissible losses for which the generator is designed, to limit the rotor heating, the generator will be under-rated for satisfactory operation. This aspect of the generator will be dealt with in chapter 4.

3.6 Summary

(1) A method for the calculation of rotor losses for a generator with any number of damper circuits is described.

(2) A simpler model of the generator with one damper on each axis is used for calculation.

(3) The circuit parameters are calculated from machine designer's data as shown in Appendix B.

(4) Rotor losses for SB and DB connections are calculated for different operating conditions.

CHAPTER 4

DERATING OF GENERATOR

In unit schemes on account of the absence of filters, current harmonics generated by the converter flow through the generators and give rise to additional losses. These additional losses in the rotor and the stator of the generators due to the flow of harmonics have been calculated in chapter 3. In order to accomodate additional losses without overheating the machines, the full load rating of the generators must be lowered. The procedure for calculating the derating factors for generators is described below using the generator described in Appendix B as an example. Derating factor is defined as:

$$\text{Derating factor} = \frac{\text{Actual rating of the machine in MW}}{\text{Normal rating of the machine in MW}}$$

4.1 Double Block Connection

The procedure for calculating the derating factor involves the computation of total losses for the stator and rotor circuits of the generators with and without harmonics respectively.

Losses (without harmonics): Under steady state conditions, damper windings carry no current. The only losses are therefore due to the rated a.c. current in the stator windings and the rated d.c. field current in the rotor field circuit and are calculated by using eqns. 3.29 and 3.0 respectively.

$$\text{stator losses} = |I_{d1}|^2 \cdot r_d + |I_{q1}|^2 r_q \qquad (r_d = r_q)$$

$$= (|I_{d1}|^2 + |I_{q1}|^2) \cdot r_d$$

$$= |I_a|^2 \cdot r_d$$

$$= (1)^2 \,.\, 0.00365 = 0.00365 \text{ p.u.}$$

$$\text{rotor field loss} = (I_f)^2 \cdot r_{ff}$$

$$= (1)^2 \,.\, 0.000702 \text{ p.u.}$$

$$\text{total losses} = 0.004352 \text{ p.u.} \qquad (4.1)$$

r_{en} = Equivalent resistance of the generator for normal operation

= 0.004352 p.u.

Losses (with harmonics): These losses include losses in stator due to rated fundamental a.c. current, losses in the field due to excitation current and additional losses in the stator and rotor circuits due to harmonics. The losses in the field circuit due to excitation current with harmonics will be more than without harmonics due to increased excitation current required to provide the reactive power which in a conventional scheme was supplied by a filter.

In case of DB connection p.f. = 0.841

p.f. for which generator is designed = 0.92

As the generator will operate at lower p.f., the reactive power demand on the generator will increase which means increased excitation. The increase in excitation in this case approximated as 1.20 x 0.09 = 0.108 p.u., where the factor 1.20 is used to take saturation into account because the generator is operating near the saturation limit and 0.09 is the change required in the generated voltage to meet the reactive power demand.

The net field current is therefore = 1.0 + 0.108

= 1.108 p.u.

$$\text{Additional stator losses} = \sum_{n=2}^{\infty} \left(\left|I_{dpn}\right|^2 \cdot r_d + \left|I_{qpn}\right|^2 \cdot r_q\right)$$

$$= 0.0000131 \quad \text{(by use of equation 3.27)} \qquad (4.2)$$

$$\text{Additional rotor losses} = \sum_{n=2}^{\infty} \left(\left|I_{fpn}\right|^2 \cdot r_{ff} + \left|I_{1dpn}\right|^2 \cdot r_{11d} + \left|I_{1qpn}\right|^2 \cdot r_{11q}\right)$$

$$= 0.0000498 \quad \text{(by use of equation 3.28)} \qquad (4.3)$$

Stator losses due to fundamental a.c. current = 0.00365 (4.4)

$$\text{Rotor field losses due to excitation current} = (1.108)^2 \cdot 0.000702$$

$$= 0.000862 \qquad (4.5)$$

Total losses with harmonics = (4.2) + (4.3) + (4.4) + (4.5)

= 0.0045749 (4.6)

r_{eh} = Equivalent resistance of generator with harmonics

= 0.0045749

The losses in equation 4.6 should not exceed the losses in equation 4.1 for satisfactory operation, therefore, value of current must go down. The new value of current is then

$$I_{1n} = \sqrt{\frac{r_{en}}{r_{eh}}} = \sqrt{\frac{0.004352}{0.0045749}} = 0.975 \text{ of normal current}$$

where I_{1n} = new current rating

Therefore new megawatt rating = 120 x 0.975 x 0.841

= 98.43 MW

Mw rating for which generator is designed = 120 x 0.92

= 110.40 MW

$$\text{Derating Factor} = \frac{98.43}{110.40} = 89.15\%$$

The above derating factor means that the generator should be loaded only to 89% of its rated capacity. As the generator is normally designed for certain negative sequence load (say 15%) and converter operation is purely balanced and symmetrical, the tolerance for negative sequence load can be used for the temperature rise in the rotor caused by harmonics. So the above calcualtions highlight the fact that the generator of normal design could be used for DB connection without any derating. The operating p.f. of the given generator is 0.92 but the generator is designed for 0.85 p.f. the reason for which may be that in the eventuality of failure of filters, the generator will be able to supply the required reactive power.

4.2 Single Block Connection

In the case of SB connection p.f. = 0.7787

p.f. for which generator is designed = 0.92

The increase in excitation approximated for this case, for the same reason as explained in section 4.1, is 1.20 x 0.15 = 0.18.

The net field current is therefore = 1.0 + 0.18 = 1.18 p.u.

Losses without harmonics = as calculated in equation 4.1

$$= 0.004352 \tag{4.7}$$

$$r_{en} = 0.004352$$

Losses with harmonics = Losses in stator due to rated fundamental a.c. current + Losses in the field due to excitation current + Additional losses due to harmonics in stator and rotor circuits

$$= 0.00365 + (1.18)^2 \times 0.000702 + 0.0012168 + 0.0003499$$

$$= 0.006194 \text{ p.u.} \tag{4.8}$$

$$r_{eh} = 0.006194$$

$$I_{1n} = \text{new current rating} = \sqrt{\frac{r_{en}}{r_{eh}}} = \sqrt{\frac{0.004352}{0.006194}}$$

$$= 0.838 \text{ of normal current}$$

$$\text{New megawatt rating} = 120 \times 0.838 \times \text{p.f.}$$

$$= 120 \times 0.838 \times 0.7787$$

$$= 78.3 \text{ MW}$$

Megawatt rating for which generator is designed = 110.40 MW.

$$\text{Derating factor} = \frac{78.3}{110.4} \times 100 = 71\%$$

It means generator should operate at 71% of its normal rating. Even if the generator is designed for (say 15%) negative sequence load, still the derating factor will be 86%.

The above figures clearly illustrate that the viable operation of unit connection is 12-pulse operation. For SB connection, the derating of the generator must be done for safe operation.

CHAPTER 5

EVALUATION OF UNIT SCHEMES

This chapter deals with the technical and economic advantages and disadvantages of unit schemes as compared to the conventional schemes. In the following discussion the word "valve" is used for thyristor valve. There are clear indications that in future development of HVDC technology only thyristor valves will be used [12]. In fact some leading manufacturers have already disbanded the manufacture of mercury-arc valves. A thyristor valve of 250 kV rating has undergone testing at the INGA-SHABA intertie in Zaire. The momentum of research in the thyristor field, as it is today, will produce thyristor of much higher voltage and current ratings. These higher ratings of valves will allow the parallel arrangement of bridges instead of series arrangement as is adopted today.

5.1 Technical Evaluation of Unit Schemes

The unit type of connections have been described in detail in Chapter 1 with illustrative figures. The main features of these connections are:

1. No a.c. filters.
2. No circuit breakers.
3. No a.c. switchyard, 138 kV or 230 kV.
4. Bridge by-pass isolator is not needed, if parallel arrangement of bridges is used[6], as shown in Fig. 5.1.

(a) Filters

A.c. harmonic filters which are used in the conventional schemes to supply some of the reactive power and to keep the harmonic distortion on the a.c. common bus to an acceptable level, are a source of a lot of technical problems such as the possibility of resonance with the local system, behaviour of filters when going off-tune, i.e. when the frequency departs from its nominal value and overvoltage during switching operation. Unit schemes do not suffer from such a drawback due to the non-provision of filters.

(b) Generators

As the filters are not provided in the unit connections, therefore the generators will have to absorb the a.c. harmonic currents, which will cause heating of rotor circuits as described in Chapter 3. The derating factor of generators has been calculated in Section 4.1. For 12-pulse operation, there is no need to derate the generator, as the tolerance for negative sequence load can be used for temperature rise in the rotor caused by harmonics. For SB connection, i.e. 6-pulse operation, the generator will have to be derated for satisfactory operation even when using the tolerance for negative sequence load, to keep the rotor losses within permissible limits. For the present day HVDC projects, 12-pulse operation is considered the most suitable technically as well as economically.

(c) Commutation Reactance and Reactive Power

Commutation reactance in the case of unit arrangement includes the generator sub-transient reactance and reactance of converter transformer, i.e. x_c increases in the case of unit arrangement which results in the poor p.f. of generator, increased reactive power demand on generator and higher excitation. Calculations for the given generator ($x_d'' = 0.24$, $x_t = 0.12$ and $\alpha = 15^\circ$) show that for DB connection, reactive power is 64.3% of the real power and for SB connection reactive power is 80% of the real power.

In the case of DB connection with the given reactances, x_c is 0.24. For $\alpha = 15^\circ$ and $x_c = 0.24$, the angle of overlap is 29.38°. For the safe operation of converter, say $u = 25^\circ$, the generator reactance x_d'' must go down which is about 0.16.

(d) Transformer

The generator transformer will also be acting as a converter transformer, so it has to be designed for overstresses due to the flow of harmonics. There is no need of tap-changers as the change in voltage will be taken care of by the excitation control of the generator.

(e) Station Control

The controls linking each generator with its converter bridge will be greatly simplified in the unit arrangement, which is quite complex for conventional arrangement. In a conventional scheme, the overall station control comprises: the co-ordination of filter control with the generator control as well as with the converter control which is very complicated.

As regards protection, the faults within the station will be cleared by the field suppression of the generator and faults on the d.c.

line will be dealt with as in the conventional scheme [illegible]. It is expected that the higher effective impedance of the system will control the level of over-current arising out of the internal faults such as valve flashover. Of course, in the case of unit schemes, the excitation system of the generator will have to be really fast and hence static excitation must invariably be used.

(f) Reliability

Due to the fault in one bridge of a DB connection, the whole out-put of that unit will be lost. Moreover, S.C. reactance of the a.c. system for unit scheme is more than the conventional scheme, so the generators over-rating capacity will be less than the conventional. On the other hand, a fault in the a.c. filters or a.c. busbar in the conventional scheme may result in the collapse of the whole system. On account of the a.c. isolation of generators, the oscillatory effect of one generator with the other is absent, so there are less stringent requirements on the regulating systems on turbines. For conventional schemes, large changes in load will bring large changes in frequency, which makes the design of the economical filter more difficult and the frequency independence of the h.v.d.c. transmission is lost. Unit connection has no such problems.

(g) Other Operational Features

With the thermal units of large out-put such as 500 MW and the development of thyristor valves of 250 - 300 kV rating, the two bridges of one 12-pulse unit may be connected in parallel with the two bridges of the other units. Such an arrangement is shown in Fig. 5.1. With the

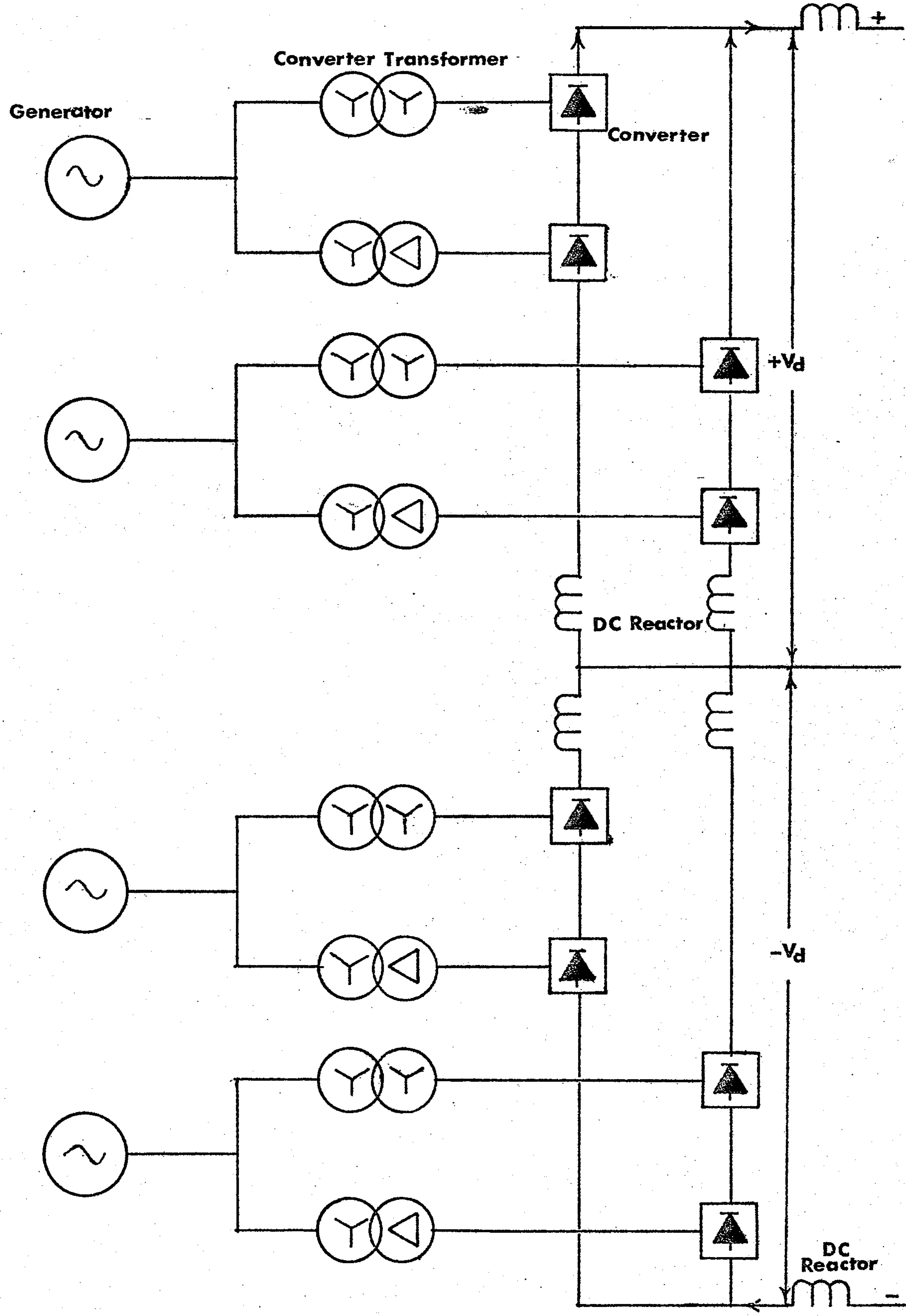


Fig. 5·1 Unit arrangement with parallel connection of bridges

parallel operation of bridges, there is no problem of insulation co-ordination as in the series connection of bridges. So, for a single bipole, the working voltage will be $\pm$ 500 - $\pm$ 600 kV. This arrangement gives a lot of flexibility for building a project in stages as each pair of bridges may be added as the unit is completed but still working with the optimum voltage of the system which gives low transmission losses and hence greater efficiency. Also each unit may be operated at different current rating. There will be some complication in the converter station control since any signal received indicating the change in current order derived from change in power order would need to be divided between parallel connected units.

For hydraulic stations, where generator units are not big enough (typical rating 100 MW) as compared to thermal units, the current rating of the thyristor for a voltage of 250 kV may not prove optimum. In that case, a combination of series and parallel arrangement of lower voltage rating bridges may be suitable.

(h) Telephone Interference

The unit scheme relies upon locating the converter station in a close proximity to the generating station. The generator-converter transformer is considered a part of the power station. So the connection from the transformer for taking the power out to the converter will be by cables and therefore no danger of telephone interference is envisaged. Most of the time, the generating station for which unit arrangement is suggested will be in remote localities, where there are no open telephone lines, hence no danger of telephone interference. This point is illustrated by an example of Radisson Station[13] in the Nelson River Development, where no restrictions are imposed to limit the telephone noise even though there is one mile of 138 kV overhead a.c. line. This follows from the fact that there are no open telephone lines in the area.

After discussing the technical aspects of unit schemes, the economic features are highlighted next in this chapter.

5.2 Economic Evaluation of Unit Schemes

The exact evaluation of a unit scheme is only possible by selecting a specific example of practical nature where the cost of each component is known. Efforts were made to obtain such a cost data so that exact cost analysis of the unit schemes may be presented in this thesis but did not succeed. The percentage cost figures presented in this thesis are based on the work done previously by others.

According to the cost estimation as shown in various manufacturers' data and technical literature, for a conventional HVDC converter station the cost of filter circuits, converter transformers and a.c. switchyard is approximately 40% [14] of the total station cost and could be saved with unit type of connections.

As is common, the cost of the generator-converter transformer is included in the power station cost and its cost could increase by a maximum of 2% of the total station cost [14].

For the generator data in this thesis, at $\alpha = 15^{\circ}$ and the rated value of current, overlap of about 29° is obtained. For the satisfactory operation of the converter (say $u = 25^{\circ}$) the reactance of the generator should be lower which is calculated as 0.16. According to various manufacturers' data, the decrease in reactance from 0.24 to 0.16 will result in a cost increase of about 8.8% of generator.

Also in the literature, it has been illustrated that for a thermal plant the increase in generator cost for the unit concept of 500 MW rating can be estimated to be 10% as compared to the conventional arrangement or an a.c. application.

In the case of parallel arrangement of bridges, no isolating switches are needed. But the control arrangement to divide the current order derived from power order between parallel connected units could offset these savings.

In the unit scheme, extra costs could occur due to special auxilliary equipment and adapted sizes of generators which would not normally be used. From the figures available[14] a 25 to 30% savings in cost of a rectifier station may be a good guess.

From the above comparison, it can be summarized that the unit arrangement of the converter station has both the technical and economic advantages over the conventional arrangement. The actual savings in cost can only be estimated by designing a project of practical nature.

5.3 Suggestions for Further Investigations

In the unit arrangement due to the flow of harmonics into the generator, there is going to be voltage distortion at the converter terminals which may effect the firing angle characteristics of the valves. The voltage distortion level at the converter terminals must be investigated to ensure proper operation of the converter.

CHAPTER 6

CONCLUSIONS

The following conclusions are drawn on the basis of the theoretical results obtained in this thesis and data collected from the literature.

1. In unit connection, due to the non-provision of filters, harmonics flow into the generator and cause additional losses in the rotor circuits.

2. A simple d-q model of synchronous generators representing the damper circuits by an equivalent coil on each axis is found satisfactory for the evaluation of additional losses due to harmonic currents.

3. A detailed representation of the dampers by nested circuits is needed when the heat loss in each bar or end ring segment is required.

4. On account of large magnitudes of 5th and 7th harmonic currents the Single-block arrangement gives rise to many times higher additional losses as compared to Double-block arrangement.

5. Harmonic currents of the order of pn $\pm$ 1 in stator windings should be taken into account for the calculation of additional losses in pairs with their proper phase angles, as these induce harmonic currents of pn order in rotor circuits for which vector addition is necessary.

6. For DB connection, generators of a conventional design could be used at 100% rating because the additional losses due to harmonics are usually less than the permissible limit for negative sequence losses.

7. For SB connections, generator must be derated for safe operation as the additional rotor losses exceed the permissible tolerance for negative sequence losses.

8. Due to the development of thyristor valves of higher voltage rating, parallel arrangement of bridges of different units is possible which is flexible and efficient for a growing system.

9. Technically, unit arrangement is reliable and less complicated as compared to conventional arrangement.

10. Unit arrangement is more economical than the conventional as the cost savings are achieved due to the elimination of a.c. harmonic filters and a.c. switchyard.

11. Cost savings of about 25 - 30% are expected from unit arrangement, the exact savings will depend upon each individual case.

12. Unit schemes appear practical and technically sound and should find application in near future.

13. Generator can be overdimensioned to take into account the additional losses caused by harmonics for a desired power out-put.

REFERENCES

(1) KIMBARK, E.W.: "Direct Current Transmission", Vol. 1, Wiley Interscience, New York, 1971.

(2) KAUFERLE, J.: "Infeed from Power Stations with Generator and Static Converter in Unit Connection", Brown Boveri Review, Vol. 60, No. 5, May 1973, pp. 205-211.

(3) CASSEN, W.: "A Technical and Economic Comparison Between A.C. and D.C. Transmission", C.I.G.R.E., 1968, Report 42/43-01, p. 42.

(4) BATEMAN, L.A., BUTLER, L.S., and HAYWOOD, R.W.: "The ± 450 kV Direct Current Transmission for the Nelson River Project", C.I.G.R.E., Report 43-02, 1968, p. 9.

(5) KRISHNAYYA, P.C.S.: "Block and Double-block Connections for HVDC Power Station Infeed", IEEE Power Engineering Society, Winter Meeting 1973, Paper No. C73227-6 PWR.

(6) CALVERLEY, T.E., OTTAWAY, C.H., and TUFNELL, D.H.A.: "Concept of a Unit Generator Converter Transmission System", International Conference on High Voltage D.C. and/or A.C. Power Transmission, 19-23 November 1973, IEE, pp. 53-59.

(7) GLEBOV, I.A.: "Additional Losses in Synchronous Generator Rotor and its Electromagnetic Moment Under Rectifier Load Operation", Electra No. 17, 1971, pp. 14-27.

(8) FITZGERALD, A.E., KINGSLEY, Jr. C., and KUSKO, A.: "Electric Machinery", Third Edition, McGraw-Hill Inc., New York, 1971.

(9) LAWRENSON, P.J., and MATHUR, R.M.: "Asynchronous performance of Reluctance Machines Allowing for Irregular Distribution of Rotor Conductors", Appendix Table 2, Proc. IEE, Vol. 119, No. 3, March 1972, pp. 324.

(10) HARRIS, M.R., LAWRENSON, P.J., and STEPHENSON, J.M.: "Per-Unit Systems With Special Reference to Electrical Machines", Cambridge University Press, 1970.

(11) BABB, D.S., and WILLIAMS, J.E.: "Network Analysis of A.C. Machine Conductors", Trans. AIEE, Vol. 70, 1951, pp. 2001-2005.

(12) MARTENSSON, H., and DANFORS, P.: "The Development of HVDC Technology at ASEA", ASEA Journal, Vol. 48, No. 3, 1975, pp. 51-54.

(13) FLETCHER, D.E., and CLARKE, C.D.: "A.C. Filters for the Nelson River Transmission Project", Proceedings of the Manitoba Power Conference EHV-DC, June 1971, Winnipeg, Canada, pp. 579-605.

(14) KRISHNAYYA, P.C.S., and LIPS, H.P.: Discussion on "Concept of a Unit Generator Converter Transmission", Discussion International Conference on High Voltage D.C. and/or A.C. Power Transmission, 19-23 November 1973, IEE, pp. 58.

APPENDIX A

Analysis of A.C. Current Harmonics by Fourier Series

Any periodic quantity may be represented by a Fourier series, the exponential form of such a series is

$$F(\theta) = \sum_{h=-\infty}^{\infty} A_h \underline{/h\theta}$$

where, $$A_h = \frac{1}{2\pi} \int_{-\pi}^{\pi} F(\theta) \underline{/-h\theta}\, d\theta$$

and, $$\underline{/h\theta} = e^{j(h\theta)} = \cos(h\theta) + j \sin(h\theta)$$

Refering to Fig. 2.2 (b), the wave-shape of the current on the a.c. side of the converter is not sinosoidal, however, wave-shape is periodic and therefore can be analyzed into a mains frequency component and higher (multiple) order harmonics by fourier series analysis. The peak value and phase of the hth harmonic are given by $2A_h$.

As defined in Kimbark[1], h is odd and also from Fig. 2.2 (b), $F(\theta) = -F(\theta + \pi)$.

Therefore, A_h can be rewritten as

$$A_h = \frac{1}{\pi} \int_{0}^{\pi} F(\theta) \underline{/-h\theta}\, d\theta$$

$$= \frac{1}{\pi} \int_{0}^{\pi} i(\theta) \underline{/-h\theta}\, d\theta$$

where, $i(\theta)$ = value of the instantaneous current.

The peak value and phase of the hth harmonic are given by

$2\,A_h$

therefore $$\sqrt{2}\,I_h = \frac{2}{\pi}\int_{\alpha-60^\circ}^{\alpha+120^\circ} i(\ )\ \underline{/-h\theta}\ d\theta$$

where I_h = complex r.m.s. value of the hth harmonic current. Here the phase angle of the harmonic current is expressed as phase advance with respect to the line to neutral voltage.

Substituting the value of $i(\theta)$ in all the four segments and applying the appropriate limits for integration.

$$\sqrt{2}\,I_h = \frac{2}{\pi}\Big[\int_{\alpha-60^\circ}^{\delta-60^\circ} \hat{I}_{s2}\,\{\cos\alpha - \cos(\theta + 60^\circ)\}\ \underline{/-h\theta}\ d\theta$$

$$+ \int_{\delta-60^\circ}^{\alpha+60^\circ} \hat{I}_{s2}(\cos\alpha - \cos\delta)\ \underline{/-h\theta}\ d\theta$$

$$+ \int_{\alpha+60^\circ}^{\delta+60^\circ} \hat{I}_{s2}\{\cos(\theta - 60^\circ) - \cos\delta\}\ \underline{/-h\theta}\ d\theta\Big]$$

therefore $$I_h = \frac{\hat{I}_{s2}}{\sqrt{2}\pi}\Big[\int_{\alpha-60^\circ}^{\delta-60^\circ} \{2\cos\alpha - 2\cos(\theta + 60^\circ)\}\ \underline{/-h\theta}\ d\theta$$

$$+ \int_{\delta-60^\circ}^{\alpha+60^\circ} 2(\cos\alpha - \cos\delta)\ \underline{/-h\theta}\ d\theta$$

$$+ \int_{\alpha+60^\circ}^{\delta+60^\circ} \{2\cos(\theta - 60^\circ) - 2\cos\delta\}\ \underline{/-h\theta}\ d\theta\Big]$$

$$\text{or}\quad \sqrt{2\pi}\,\frac{I_h}{\hat{I}_{s2}} = \int_{\alpha-60^\circ}^{\alpha+60^\circ} 2\cos\alpha\,\underline{/-h\theta}\,d\theta - \int_{\alpha-60^\circ}^{\delta-60^\circ} 2\cos(\theta+60^\circ)\underline{/-h\theta}\,d\theta$$

$$+ \int_{\alpha+60^\circ}^{\delta+60^\circ} 2\cos(\theta-60^\circ)\underline{/-h\theta}\,d\theta - \int_{\delta-60^\circ}^{\delta+60^\circ} 2\cos\delta\,\underline{/-h\theta}\,d\theta$$

from trigonometry

$$2\cos\theta = \underline{/\theta} + \underline{/-\theta} \qquad \underline{/\theta} = e^{j\theta}$$

therefore $2\cos\alpha = \underline{/\alpha} + \underline{/-\alpha}$

$$2\cos(\theta + 60^\circ) = \underline{/\theta + 60^\circ} + \underline{/-\theta - 60^\circ}$$

$$2\cos(\theta - 60^\circ) = \underline{/\theta - 60^\circ} + \underline{/-\theta + 60^\circ}$$

$$2\cos\delta = \underline{/\delta} + \underline{/-\delta}$$

therefore

$$\sqrt{2\pi}\,\frac{I_h}{I_{s2}} = \int_{\alpha-60^\circ}^{\alpha+60^\circ} (\underline{/\alpha} + \underline{/-\alpha})\underline{/-h\theta}\,d\theta - \int_{\alpha-60^\circ}^{\delta-60^\circ} (\underline{/\theta + 60^\circ}) + \underline{/-\theta - 60^\circ})\underline{/-h\theta}\,d\theta$$

$$+ \int_{\alpha+60^\circ}^{\delta+60^\circ} (\underline{/\theta - 60^\circ} + \underline{/60^\circ - \theta})\underline{/-h\theta}\,d\theta - \int_{\delta-60^\circ}^{\delta+60^\circ} (\underline{/\delta} + \underline{/-\delta})\underline{/-h\theta}\,d\theta$$

$$= \int_{\alpha-60^\circ}^{\alpha+60^\circ} (\underline{/\alpha - h\theta} + \underline{/-\alpha-h\theta})d\theta - \int_{\alpha-60^\circ}^{\delta-60^\circ} (\underline{/(1-h)\theta + 60^\circ} + \underline{/-(h+1)\theta - 60^\circ})d\theta$$

$$+ \int_{\alpha+60^\circ}^{\delta+60^\circ} (\underline{/-60^\circ - (h-1)\theta} + \underline{/60^\circ - (h+1)\theta})d\theta - \int_{\delta-60^\circ}^{\delta+60^\circ}$$

$$(\underline{/\delta-h\theta} + \underline{/-\delta-h\theta})\,d\theta$$

$$= \frac{j}{h}\left[\underline{/\alpha - h\theta} + \underline{/-\alpha - h\theta}\right]_{\alpha-60^\circ}^{\alpha+60^\circ} + \left[-\frac{j}{(h-1)}\underline{/60^\circ - (h-1)\theta} - \frac{j}{(h+1)}\;\cdot\right.$$

$$\left.\underline{/-60^\circ - (h+1)\theta}\right]_{\delta-60^\circ}^{\delta-60^\circ}$$

$$+ \left[\frac{j}{(h-1)}\,\underline{/-60^\circ - (h-1)\theta} + \frac{j}{(h+1)}\,\underline{/60^\circ - (h+1)\theta}\right]_{\alpha+60^\circ}^{\delta+60^\circ}$$

$$+ \left[-\frac{j}{h}\,\underline{/\delta - h\theta} - \frac{j}{h}\,\underline{/-\delta - h\theta}\right]_{\delta-60^\circ}^{\delta+60^\circ}$$

$$= \frac{j}{h}\,\underline{/\alpha - h\alpha - h60^\circ} + \frac{j}{h}\,\underline{/-\alpha - h\alpha - h60^\circ} - \frac{j}{h}\,\underline{/\alpha - h\alpha + h60^\circ} - \frac{j}{h}\,\underline{/-\alpha - h\alpha + h60^\circ}$$

$$- \frac{j}{h}\,\underline{/\delta - h\delta - h60^\circ} - \frac{j}{h}\,\underline{/-\delta - h\delta - h60^\circ} + \frac{j}{h}\,\underline{/\delta - h\delta + h60^\circ} + \frac{j}{h}\,\underline{/-\delta - h\delta + h60^\circ}$$

$$- \frac{j}{(h-1)}\,\underline{/-(h-1)\delta + h60^\circ} - \frac{j}{(h+1)}\,\underline{/-(h+1)\delta + h60^\circ} + \frac{j}{(h-1)}\;\cdot$$

$$\underline{/-(h-1)\alpha + h60^\circ} + \frac{j}{(h+1)}\,\underline{/-(h+1)\alpha + h60^\circ}$$

$$+ \frac{j}{(h-1)}\,\underline{/-(h-1)\delta - h60^\circ} + \frac{j}{(h+1)}\,\underline{/-(h+1)\delta - h60^\circ} - \frac{j}{(h-1)}\;\cdot$$

$$\underline{/-(h-1)\alpha - h60^\circ} - \frac{j}{(h+1)}\,\underline{/-(h+1)\alpha - h60^\circ}$$

$$= \frac{j}{h}\,\underline{/-(h-1)\alpha}\,(\underline{/-h60^\circ} - \underline{/h60^\circ}) + \frac{j}{h}\,\underline{/-(h+1)\alpha}\,(\underline{/-h60^\circ} - \underline{/h60^\circ})$$

$$+ \frac{j}{h}\,\underline{/-(h-1)\delta}(\underline{/h60^\circ} - \underline{/-h60^\circ}) + \frac{j}{h}\,\underline{/-(h+1)\delta}(\underline{/h60^\circ} - \underline{/-h60^\circ})$$

$$+ \frac{j}{(h-1)}\,\underline{/-(h-1)\delta}\,(\underline{/-h60^\circ} - \underline{/h60^\circ}) + \frac{j}{(h+1)}\,\underline{/-(h+1)\delta}\,(\underline{/-h60^\circ} - \underline{/h60^\circ})$$

$$+ \frac{j}{(h-1)}\,\underline{/-(h-1)\alpha}\,(\underline{/h60^\circ} - \underline{/-h60^\circ}) + \frac{j}{(h+1)}\,\underline{/-(h+1)\alpha}\,(\underline{/h60^\circ} - \underline{/-h60^\circ})$$

$$\sqrt{2\pi}\,\frac{I_h}{\hat{I}_{s2}} = j(\underline{/h60^\circ} - \underline{/-h60^\circ})\Big[-\frac{\underline{/-(h-1)\alpha}}{h} - \frac{\underline{/-(h+1)\alpha}}{h} + \frac{\underline{/-(h-1)\delta}}{h} + \frac{\underline{/-(h+1)\delta}}{h}$$

$$- \frac{\underline{/-(h-1)\delta}}{(h-1)} - \frac{\underline{/-(h+1)\delta}}{(h+1)} + \frac{\underline{/-(h-1)\alpha}}{(h-1)} + \frac{\underline{/-(h+1)\alpha}}{(h+1)}\Big]$$

$$= \frac{j}{h}\,(\underline{/h60^\circ} - \underline{/-h60^\circ})\Big[\frac{\underline{/-(h-1)\alpha} - \underline{/-(h-1)\delta}}{(h - 1)} - \frac{\underline{/-(h+1)\alpha} - \underline{/-(h+1)\delta}}{(h + 1)}\Big]$$

$$I_h = \frac{\sqrt{2}}{\pi}\,\hat{I}_{s2}\,\sin(h60^\circ)\Big[\frac{\underline{/-(h+1)\alpha} - \underline{/-(h+1)\delta}}{(h + 1)} - \frac{\underline{/-(h-1)\alpha} - \underline{/-(h-1)\delta}}{(h - 1)}\Big]$$

APPENDIX B

SYNCHRONOUS GENERATOR DATA

Generator Designer's Data

MVA = 120.0	x_{potier} = 0.171 p.u.
MW = 102.0	x_d = 1.106 p.u.
p.f = 0.85	x_q = 0.642 p.u.
kV = 13.80	x'_d = 0.301 p.u.
RPM = 90	x''_d = 0.233 p.u.
s.c. Ratio = 1.0	x''_q = 0.242 p.u.
E(MW-sec) = 410.39	x_2 = 0.231 p.u.
H(MW-sec/MVA) = 3.42	x_0 = 0.165 p.u.
H Factor = 26.31	T''_d = 0.0395 sec.
T_a = 0.712 sec.	T'_{d0} = 4.105 sec.
T'_d = 1.123 sec.	T''_{d0} = 0.0195 sec.
ω = 377 rad/sec.	T''_{q0} = 0.048 sec.

Data for Parameters

Direct-axis	Quadrature-axis
x_{ad} = 0.935 p.u.	x_{aq} = 0.471 p.u.
x_{a1d} = 0.935 p.u.	r_{11q} = 0.03065 p.u.
x_{f1d} = 0.935 p.u.	x_{11q} = 0.55460 p.u.
x_{ffd} = 1.08599 p.u.	r_q = 0.00365 p.u.
r_{11d} = 0.03469 p.u.	
x_{11d} = 1.05353 p.u.	
r_d = 0.00365 p.u.	
r_{ffd} = 0.000702 p.u.	

Machine Designer's Data

Reactances: x_d, x_q, x_1, x_d', x_d'', x_q''

Time constants: T_a, T_d'', T_{d0}', T_{d0}'', T_{q0}'', T_d'

Inertia: H

Resistances: r (could be calculated if T_a is specified)

Constants to be Derived

Reactances: x_d, x_q, x_{ad}, x_{ffd}, x_{11d}, x_{11q}, x_{aq}

Resistances: r, r_{fd}, r_{1d}, r_{1q}

Inertia: H, not needed in the thesis

Definitions of Machines Designer's Data

Derived reactances (in p.u. of rated volts and MVA)

$$x_d = x_\ell + x_{ad} \tag{B.1}$$

$$x_d' = x_\ell + (x_{ad} \,//\, x_{fd}) \tag{B.2}$$

$$x_d'' = x_\ell + (x_{ad} \,//\, x_{fd} \,//\, x_{1d}) \tag{B.3}$$

$$x_q = x_\ell + x_{aq} \tag{B.4}$$

$$x_q'' = x_\ell + (x_{aq} \,//\, x_{1q}) \tag{B.5}$$

Time-Constants (Seconds)

d-axis transient $T'_{d0} = \frac{(x_{fd} + x_{ad})}{\omega \cdot r_{fd}}$ (B.6)

d-axis sub-transient $T''_{d0} = \frac{x_{1d} + x_{ad} \,//\, x_{fd}}{\omega \cdot r_{1d}}$ (B.7)

q-axis sub-transient $T''_{q0} = \frac{x_{1q} + x_{aq}}{\omega_0 \cdot r_{1q}}$ (B.8)

Armature $T_a = \frac{x''_d + x''_q}{2.r.\omega}$ (B.9)

The equivalent circuit of the d-q axis model of the synchronous generator is shown in Fig. 3.1.

Reactances

$\underline{x_{ad}}$ $\quad \underline{\underline{x_{ad}}} = x_d - x_\ell$ (B.10)

$\underline{x_{ffd}}$ $\quad \underline{\underline{x_{ffd}}} = x_{ad} + x_{fd}$ (B.11)

$$x'_d = x_\ell + \frac{x_{ad} \cdot x_{fd}}{x_{ad} + x_{fd}}$$

from which

$$x_{fd} = -x_{ad} \frac{(x'_d - x_\ell)}{x'_d - x_\ell - x_{ad}}$$

$$= - \frac{(x_d - x_\ell)(x'_d - x_\ell)}{x'_d - x_\ell - x_d + x_\ell}$$

$$= - \frac{(x_d - x_\ell)(x'_d - x_\ell)}{(x'_d - x_d)}$$

$$= \frac{(x_d - x_\ell)(x'_d - x_\ell)}{(x_d - x'_d)}$$ (B.12

$$x_{ffd} = x_{ad} + x_{fd}$$

$$= \frac{(x_d - x_\ell)^2}{(x_d - x'_d)} \qquad \text{(B.13)}$$

<u>x_{11d}</u> $\qquad x''_d = x_\ell + x_{ad} \; // \; x_{fd} \; // \; x_{1d}$ from equation (B.3)

$$= x_\ell + \frac{x_{ad} \cdot x_{fd} \cdot x_{1d}}{x_{ad}\, x_{fd} + x_{fd}\, x_{1d} + x_{1d}\, x_{ad}}$$

Solving for x_{1d}

$$x_{1d} = \frac{(x''_d - x_\ell)\left(\frac{x_{ad} \quad x_{fd}}{x_{ad} + x_{fd}}\right)}{\frac{x_{ad} \quad x_{fd}}{(x_{ad} + x_{fd})} - (x''_d - x_\ell)}$$

from equation B.2

$$x'_d - x_\ell = \frac{x_{ad} \cdot x_{fd}}{x_{ad} + x_{fd}}$$

Now substituting in the above equation

$$x_{1d} = \frac{(x''_d - x_\ell)(x'_d - x_\ell)}{(x'_d - x_\ell) - (x''_d - x_\ell)}$$

By definition of x_{11d}

$$x_{11d} = x_{ad} + x_{1d}$$

$$= (x_d - x_\ell) + \frac{(x''_d - x_\ell)(x'_d - x_\ell)}{(x'_d - x_\ell) - (x''_d - x_\ell)} \qquad \text{(B.14)}$$

$\underline{x_{aq}}$

$$x_{aq} = x_q - x_\ell \tag{B.15}$$

$\underline{x_{11q}}$

From equation B.5

$$x''_q = x_\ell + (x_{aq} \,//\, x_{1q})$$

$$= x_\ell + \frac{x_{aq} \cdot x_{1q}}{(x_{aq} + x_{1q})}$$

Solving for x_{1q} gives

$$x_{1q} = \frac{x_{aq} \quad (x''_q - x_\ell)}{x_{aq} - (x''_q - x_\ell)}$$

Substituting for x_{aq} from eqn. B.15

$$x_{1q} = \frac{(x_q - x_\ell)(x''_q - x_\ell)}{(x_q - x''_q}$$

By definition

$$x_{11q} = x_{aq} + x_{1q}$$

$$= (x_q - x_\ell) + \frac{(x_q - x_\ell)(x''_q - x_\ell)}{(x_q - x''_q)}$$

$$= \frac{(x_q - x_\ell)^2}{(x_q - x''_q)} \qquad \text{(B.16}$$

$\underline{r_{fd}}$ from equation B.6

$$r_{fd} = \frac{x_{ffd}}{\omega \,.\, T'_{d0}} \tag{B.17}$$

$\underline{r_{11d}}$ from equation B.7

$$r_{11d} = \frac{x_{1d} + x_{ad} \,//\, x_{fd}}{\omega \,.\, T''_{d0}} \tag{B.18}$$

$\underline{r_{11q}}$ from equation B.8

$$r_{11q} = \frac{x_{11q}}{\omega \,.\, T''_{q0}} \tag{B.19}$$

r from equation B.9

$$r = \frac{x''_d + x''_q}{2 \,.\, \omega \,.\, T_a} \tag{B.20}$$

In p.u. system $r = r_d = r_q$

$$r_d = r_q = \frac{x''_d + x''_q}{2 \,.\, \omega \,.\, T_a} \tag{B.21}$$

APPENDIX C

```
( JAN 75 )                          OS/360   FORTRAN H EXTENDED                  DATE

PTIONS:  ,EB,,,,OBJ,,MAP,,GOSTMT,,,S,NAME(MAIN),OPT(0),LC(654),AD(NONE),FLAG(I

EFFECT:  NAME(MAIN) NOOPTIMIZE LINECOUNT(654) SIZE(MAX) AUTODBL(NONE)
         SOURCE EBCDIC NOLIST NODECK OBJECT MAP NOFORMAT GOSTMT NOXREF NOALC N

      COMPLEX IH,CMPLX,CEXP,SA,SB,XQ,I1FU,VT,E1,VD,A2,A3,C2,C3,B2,B3,
     1D2,D3,IDH,IQH,IDN,IQN,IFN,I1DN,I1QN,A11,A22
      REAL II,I1,I2,I3,I4,I5,IDC,LOADA,LOAD1,LOAD2,LOAD3
      REAL IK
      DIMENSION IH(40),II(40),PHI(40),SYD(40),SYQ(40),SA(40),SB(40),
     1IDH(40),IQH(40),AL(10),IDC(101),DEL(101),LOADA(101),STATL(101),
     2ROTL(101),VDC(101),LOAD1(101),LOAD2(101),LOAD3(101),ROTLI(101),
     3ROTL2(101),ROTL3(101)
      DIMENSION H5(3,110),H7(3,110),H11(3,110),H13(3,110),H17(3,110),
     1H19(3,110),H23(3,110),H25(3,110),H29(3,110),H31(3,110),H35(3,110),
     2H37(3,110)
      DIMENSION COMM(110)
      DIMENSION IBUF(7000),XP(103),YP(103)
      READ(5,101)(AL(I),I=1,3)
  101 FORMAT(3F10.7)
      READ(5,102)(IDC(I),I=1,101)
  102 FORMAT(16F5.2)
       READ(5,105)XAD,XA1D,XF1D,XFF,R11D,X11D,RD,RFD,XAQ,R11Q,X11Q,RQ
  105 FORMAT(8F10.7)
      XQ=CMPLX(0.,0.642)
      XT=0.12
      XDD=0.2375
      XPU=XT+XDD
      PI=3.141593
C     ALPHA---ANGLE OF DELAY
C     U---ANGLE OF OVERLAP
C     DEL---GEN LOAD ANGLE
C     VALUE OF IDC IS IN P.U. ON GEN MVA
C     VT=1.0 P.U.--TERMINAL VOLTAGE OF GEN
      DO 10 I=1,3
      ALPHA=AL(I)
      DO 20 J=1,101
      A=COS(ALPHA)-(IDC(J)*XPU*PI/3.)
      U=ARCOS(A)-ALPHA
      COMM(J)=U*180./PI
      PHI1=ARCOS(0.5*(COS(ALPHA)+COS(ALPHA+U)))
C      I1FU---FUNDAMENTAL COMP OF A.C.
      I1FU=IDC(J)*CMPLX(COS(PHI1),-SIN(PHI1))
      DELTA=ALPHA+U
C     FROM THE VECTOR DIAGRAM FOR GEN
      VT=CMPLX(1.0,0.0)
      VD=XQ*I1FU
      E1=VT+VD
      DEL(J)=ATAN2(AIMAG(E1),REAL(E1))
      VDC(J)=VT*COS(PHI1)
      LOADA(J)=DEL(J)*180/PI
      ROTL(J)=0.0
      STATL(J)=0.0
      DO 30 K=1,6
      N1=6*K-1
      N2=6*K+1
      IDN=0.
      IQN=0.
      DO 40 N=N1,N2,2
      DD=COS(ALPHA)-COS(ALPHA+U)
      AA=(IDC(J)*SQRT(2.)*SIN(N*1.047197))/(SQRT(6.)*DD*N)
      A1=-(N+1)*ALPHA
      B1=-(N-1)*ALPHA
      A2=CMPLX(0.,A1)
```

```
      B2=CMPLX(0.,B1)
      A3=CEXP(A2)
      B3=CEXP(B2)
      C1=-(N+1)*DELTA
      D1=-(N-1)*DELTA
      C2=CMPLX(0.,C1)
      D2=CMPLX(0.,D1)
      C3=CEXP(C2)
      D3=CEXP(D2)
      IH(N)=AA*((A3-C3)/(N+1)-(B3-D3)/(N-1))
      X=REAL(IH(N))
      Y=AIMAG(IH(N))
      PHI(N)=ATAN2(Y,X)
      II(N)=CABS(IH(N))
      SYD(N)=-PHI(N)+DEL(J)-PI/2
      IF(N.EQ.N2) SYD(N)=-PHI(N)-DEL(J)+PI/2
      SYQ(N)=-PHI(N)+DEL(J)
      IF(N.EQ.N2) SYQ(N)=-PHI(N)-DEL(J)
      SA(N)=CMPLX(0.,SYD(N))
      SB(N)=CMPLX(0.,SYQ(N))
      IDH(N)=II(N)*CEXP(SA(N))
      IQH(N)=II(N)*CEXP(SB(N))
      IDN=IDN+IDH(N)
      IQN=IQN+IQH(N)
   40 CONTINUE
C     ROTOR RESISTANCE CHANGES WITH FREQUENCY
C     ROTOR RESISTANCE HAS BEEN MODIFIED BY A FACTOR OF SQRT(6*K)
C     TO ACCOUNT FOR SKIN EFFECT----EFFECTIVE ROTOR RESISTANCE
      IK=6.*K
      A11=CMPLX(XFF,-RFD/SQRT(IK))
      A12=XF1D
      A21=A12
      A22=CMPLX(X11D,-R11D/SQRT(IK))
      B11=XAQ
      B12=CMPLX(X11Q,-R11Q/SQRT(IK))
C     IFN,I1DN,I1QNCURRENTS INDUCED IN ROTOR CKTS OF 6*K FREQUENCY
      IFN=(IDN*(XA1D*A12-XAD*A22))/(A11*A22-A21*A12)
      I1DN=((-IDN*XAD)-(A11*IFN))/A12
      I1QN=(-B11*IQN)/B12
C     ROTL=ROTOR LOSSES
C     STATL= STATOR LOSSES
      I1=CABS(IDN)
      I2=CABS(IQN)
      I3=CABS(IFN)
      I4=CABS(I1DN)
      I5=CABS(I1QN)
       RT=SQRT(IK)*((I3)**2.*RFD+(I4)**2.*R11D+(I5)**2.*R11Q)
       ST=SQRT(IK)*((I1)**2.*RD+(I2)**2.*RQ)
      STATL(J)=STATL(J)+ST
      ROTL(J)=ROTL(J)+RT
   30  CONTINUE
      IF(I.EQ.1) GO TO 1
      IF(I.EQ.2) GO TO 2
      IF(I.EQ.3) GO TO 3
    1 ROTL1(J)=ROTL(J)
      LOAD1(J)=LOADA(J)
      GO TO 20
    2 ROTL2(J)=ROTL(J)
      LOAD2(J)=LOADA(J)
      GO TO 20
    3 ROTL3(J)=ROTL(J)
      LOAD3(J)=LOADA(J)
   20 CONTINUE
   10 CONTINUE
      CALL PLOTS(IBUF,7000)
      CALL PLOT(0.,-11.,23)
```

```
            CALL PLOT(0.,1.,23)
            XP(102)=0.0
            XP(103)=0.3
            YP(102)=0.0
            YP(103)=0.0004
            CALL DRAG(5.,7.,0.,0.3,0.,0.0004)
            CALL SYMBOL(0.5,8.,0.14,28HROTOR LOSS VS DIRECT CURRENT,0.,28
            CALL SYMBOL(1.,7.5,0.14,16HBLOCK CONNECTION,0.,16)
            DO 700 I=1,3
            DO 710 J=1,101
            GO TO (720,730,740),I
       720  YP(J)=ROTL1(J)
            GO TO 750
       730  YP(J)=ROTL2(J)
            GO TO 750
       740  YP(J)=ROTL3(J)
       750  XP(J)=IDC(J)
       710  CONTINUE
            IF(I.EQ.1) GO TO 760
            IF(I.EQ.2) GO TO 770
            IF(I.EQ.3) GO TO 780
       760  CALL LINE(XP,YP,101,1,10,2)
            GO TO 700
       770  CALL LINE(XP,YP,101,1,10,3)
            GO TO 700
       780  CALL LINE(XP,YP,101,1,10,5)
       700  CONTINUE
            CALL PLOT(8.,0.,-3)
            XP(102)=0.0
            XP(103)=0.3
            YP(102)=0.0
            YP(103)=5.0
            CALL DRAG(5.,7.,0.0,0.3,0.0,5.0)
            CALL SYMBOL(0.5,8.,0.14,28HLOAD ANGLE VS DIRECT CURRENT,0.,28
            CALL SYMBOL(1.,7.5,0.14,16HBLOCK CONNECTION,0.,16)
            DO 800 I=1,3
            DO 810 J=1,101
            GO TO (820,830,840),I
       820  YP(J)=LOAD1(J)
            GO TO 850
       830  YP(J)=LOAD2(J)
            GO TO 850
       840  YP(J)=LOAD3(J)
       850  XP(J)=IDC(J)
       810  CONTINUE
            IF(I.EQ.1) GO TO860
            IF(I.EQ.2) GO TO 870
            IF(I.EQ.3) GO TO 880
       860  CALL LINE(XP,YP,101,1,10,2)
            GO TO 800
       870  CALL LINE(XP,YP,101,1,10,3)
            GO TO 800
       880  CALL LINE(XP,YP,101,1,10,5)
       800  CONTINUE
            CALL PLOT(8.,0.,999)
            STOP
            END
```

```
      SUBROUTINE DRAG(XL,YL,XMIN,XINC,YMIN,YINC)
      DIMENSION XP(103),YP(103)
      CALL AXIS(0.,0.,'     ',-3,XL,0.,XMIN,XINC)
      CALL AXIS(0.,YL,'     ',3,XL,0.,XMIN,XINC)
      CALL AXIS(0.,0.,'     ',3,YL,90.,YMIN,YINC)
      CALL AXIS(XL,0.,'     ',-3,YL,90.,YMIN,YINC)
      N=XL+1.
      M=YL+1.
      DX=XL*XINC/100.
      DY=YL*YINC/100.
      XP(102)=XMIN
      YP(102)=YMIN
      XP(103)=XINC
      YP(103)=YINC
      DO 40 I=1,N
      DO 50 J=1,101
      XP(J)=(I-1)*XINC+XMIN
   50 YP(J)=(J-1)*DY+YMIN
      CALL LINE(XP,YP,101,1,0,0)
   40 CONTINUE
      DO 60 I=1,M
      DO 70 J=1,101
      XP(J)=(J-1)*DX+XMIN
   70 YP(J)=(I-1)*YINC+YMIN
      CALL LINE(XP,YP,101,1,0,0)
   60 CONTINUE
      RETURN
      END
```

```
LEVEL 2.1  ( JAN 75 )            DRAG              OS/360  FORTRAN H EXTENDED

                                                          /    DRAG /      SIZE OF

     NAME    TAG    TYPE   ADD.          NAME    TAG    TYPE   ADD.         NAME
        I SF        I*4    000178           J SF        I*4    00017C          M SF
       DX SF        R*4    000188          DY SF        R*4    00018C         XL SF
       YL SFA       R*4    000194          YP SFA       R*4    000348       AXIS SF
     LINE SF   XF          000000        XINC SFA       R*4    00019C       XMIN SF
     YMIN SFA       R*4    0001A8
```