AN ANALYSIS OF CERTAIN ASPECTS OF FORCED COMMUTATED HVDC INVERTERS

A Thesis
Presented To
The Faculty of Graduate Studies
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In Partial Fulfillment
of the Requirements for the Degree
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by
Aniruddha Gole
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ABSTRACT

Inverters used for HVDC application today are 'naturally' or 'line' commutated, which means that the line-line voltage on the ac side is used to force the current in the off-going valve to zero, thereby turning it off. In the 'forced' or 'artificially' commutated inverter, the valve current is forced to zero artificially, *i.e.*, without the use of the line-line voltage for this purpose.

By using forced commutation in HVDC inverters, it may be possible to reduce the inverter's reactive power requirement, and indeed, sometimes it is even possible to make the inverter supply reactive power.

Previous researchers have concluded that the series capacitor commutation scheme (out of the many schemes available for forced commutation) seems most promising, and have carried out certain investigations into the operation of such a series capacitor commutated inverter.

This investigation is an extension of previous work done, and covers factors such as harmonics, ac-side faults, the rate of change of firing angle and the possibility of inverting into weak ac systems.

The results indicate that the firing angle can be changed fast, that the system is immune to ac-side faults, and that it can operate satisfactorily into weak ac systems.

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a, b, c	phase sequence
c_a, c_b, c_c	capacitors in phases a, b, c
e_a, e_b, e_c	phase voltages
e_1, e_2	phase voltages involved in commutation from a typical phase 1 to phase 2.
i_a, i_b, i_c	phase currents
I_d	dc current
k	minimum number of steps needed to effect a firing angle change
ℓ	transformer inductance
P	real power
Q	reactive power
r	resistance of weak system
SCR	Short Circuit Ratio
S_0, S_1, etc.	switches
t	time
T_1, T_2, T_3 etc.	thyristors
v_a, v_b, v_c	phase voltages (same as e_a, e_b, e_c)
v_{c_1}, v_{c_2}	capacitor voltages involved in commutation from phase 1 to phase 2
V_d	dc voltage
X_c	capacitor reactance
X_ℓ	transformer/and or system reactance
α	firing angle
α_o, α_f	initial and final values of firing angle
μ	overlap angle
ω	angular frequency of supply voltage
δ	symmetrical angular change for α

CHAPTER 1

INTRODUCTION

1.1 Forced vs Natural Commutation

The thyristor valve is a device which requires the current to be brought to zero and a reverse bias across it in order to turn off when it is conducting. In the HVDC inverter this is usually provided by the line voltage itself, the process being known as 'natural' or 'line commutation'. Alternatively, this reverse biasing voltage could be derived from some other source (usually some capacitors precharged to proper voltages), the resulting commutation being called 'forced' or 'artificial' commutation.

Figure 1.1.1 shows the basic three-phase Graetz bridge used in HVDC rectification/inversion, and Fig. 1.1.2 shows the resulting waveform. The dc line is assumed to carry constant current (a justifiable assumption because of the high value of inductance in the dc circuit). The thyristors are pulsed according to their sequence, *i.e.*, 1, 2, ..., 6, each after a 60° interval. The firing angle α is measured from the phase voltage crossover. From Fig. 1.1.2 it can be seen that the current fundamental lags the ac voltage by an angle equal to $180° - \alpha$. The angle α cannot be increased to (or beyond) $180°$, because proper thyristor turn off requires that a reverse voltage exist across the thyristor for at least a minimum duration δ. Thus the maximum angle at which the bridge may be operated is given by $\alpha = 180° - \delta - \mu$ where μ (not shown in the figure) corresponds to the time required for current transfer from one phase to the other. μ is normally of the order 15° -

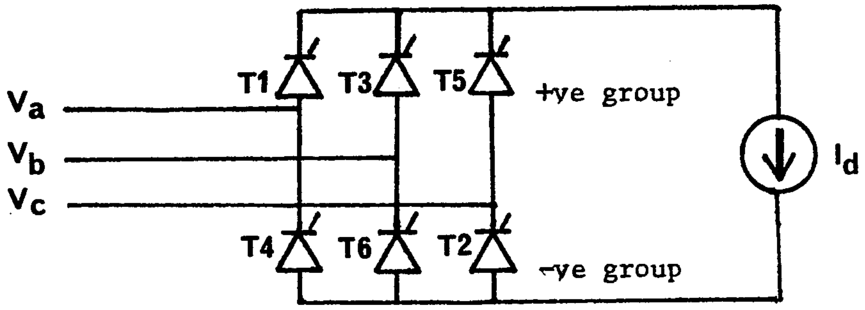


FIG 1.1.1 : THREE PHASE GRAETZ BRIDGE

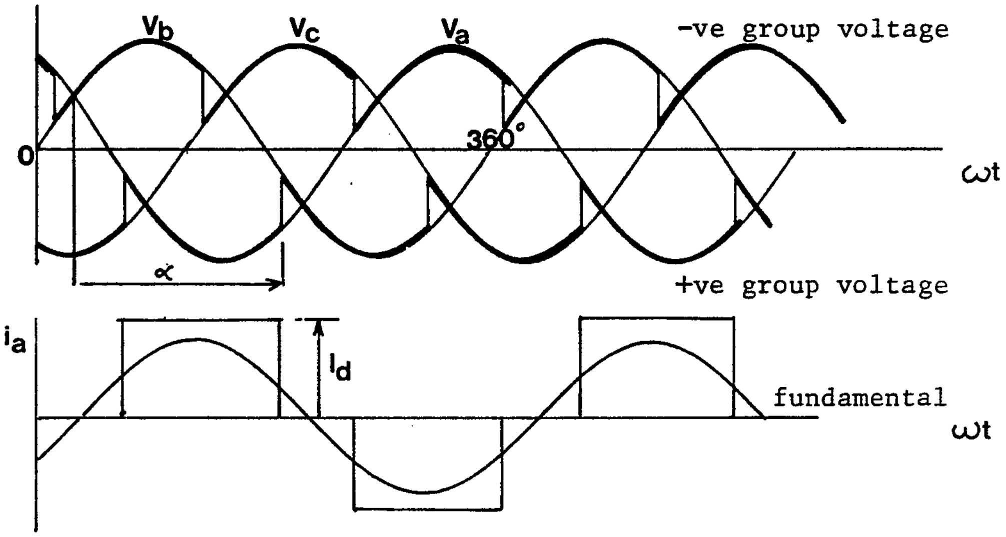
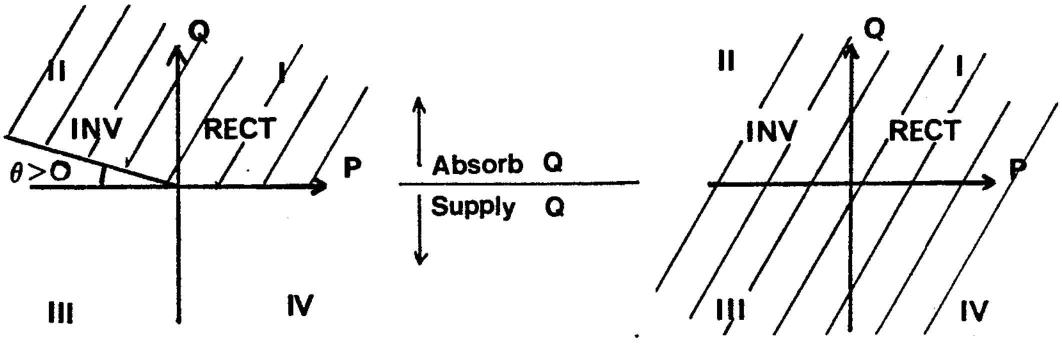


FIG 1.1.2 : VOLTAGE AND AC CURRENT WAVEFORMS.
(COMMUTATION ~~REACTANCE~~ IGNORED.)



a)NATURAL COMMUTATION b)FORCED COMMUTATION

FIG 1.1.3 : RANGES OF OPERATION

25° and arises due to the presence of finite inductance in the transformer windings. Hence α can be increased only to 150° - 155°, and this implies that the inverter must consume reactive power. A large requirement of reactive power means a drop in the system voltage, unless that reactive power is somehow supplied. In the case of the naturally commutated inverter, this reactive power may be as high as 60% of the real power. This is clear from the 4 quadrant diagram of Fig. 1.1.3(a) which shows the possible P (real power) and Q (reactive power) ranges for the naturally commutated inverter. In the inverter operation $Q = 0$ is not possible due to the extinction angle required.

In forced commutation, artificial means are used to keep the off-going thyristor reverse biased even when the line-line voltage has reversed. Thus, the firing angle may be greater than that possible under natural commutation, thereby resulting in a smaller reactive power requirement for the converter.

In fact, as shown in Fig. 1.1.3(b) reactive power (Q) supply is also possible and ideally it may be possible to operate in all four quadrants. Usually the load connected at the inverter station consumes Q. Thus, a Q supply from the inverter can be used to meet this demand, and hence allow for voltage control at the inverter bus.

Note that the 4 quadrant diagrams are drawn for inverter as well as rectifier operation because there is no reason why an inverter may not be operated as a rectifier, *i.e.*, with $\alpha < 90°$.

1.2 Why Forced Commutation?

The need for reactive power supply from the ac side is a serious drawback in the naturally commutated inverter, and this drawback is not present in the forced commutated one.

Thus with a forced commutated inverter, it is no longer necessary to invert into a strong ac system, and this may considerably increase the number of situations in which dc may be a favourable alternative over ac transmission. For example, the proposed Hong Kong-Macao link could have a force commutated converter at Macao. As the island of Macao has no generation potential and as ac links from mainland Hong Kong are impossible due to the presence of a body of water in between, HVDC transmission with static compensation at the receiving end has been proposed. But this receiving inverter may as well be a forced commutated one, thereby removing the need for any kind of reactive power compensation.

The forced commutated inverter has the feasibility of being used as a self-contained tap on an HVDC line, as it can invert into a load that has no voltage support on its ac side at all. Because it is completely solid-state it appears to be a favourable alternative to other proposed methods, such as the one by Bowles et al [1] which makes use of a dc motor - ac generator set running off the dc line to provide reactive power support. In fact recently, Sood et al [2] have done preliminary simulator tests to demonstrate inversion into lagging pf loads.

A forced commutated tap on a long HVDC line might have been a possible answer to the recently scrapped proposal of running an HVDC line between the Canadian province of Manitoba and the U.S. state of Nebraska. The proposal was cancelled due to the fact that the states of North and South Dakota could not get any power out of the line passing through them because of the inability of having a tap on the line.

Other advantages result which are a consequence of the type of forced commutation scheme used, and will be discussed in later chapters.

1.3 Requirements of a Forced Commutation Scheme

Some work has been carried out in the area of forced commutation [3,5]. The requirements that a forced commutated inverter must satisfy are thus summarized.

1. High reliability
2. Minimal stress on converter components
3. Fast change of firing angle (α) should be possible. The commutation circuit should not slow down the speed with which α can be changed. Fast control on α is required for good transient and fault performance.
4. Easy system recovery in case of fault

   The converter must resume normal operation after a fault is cleared. It should also be possible to connect/disconnect the converter to/from the system in minimum time.
5. Wide range of operation

   The converter should be able to operate over a wide range of power and current settings without commutation failure.

It may not be possible to meet all the above requirements equally well, but the system must conform to them as well as possible, without being unduly expensive.

1.4 Selection of Forced Commutation Scheme

A large number of schemes already exist [4] in the low power area, *i.e.*, in drives for ac machines. Most of these are quite complicated and are usually for voltage control, and have to operate over a large range of frequency. HVDC inverters do not have to satisfy this requirement, but they have to be extremely reliable over their operating current/power range. Thus, the requirements for high power and low power inverters are somewhat different. Some schemes proposed for HVDC applications are reviewed briefly below; and it appears that the series commutated inverter is the best.

1.4.1 Forced Commutation in Two Steps

This scheme, shown in Fig. 1.4.1, has been recommended for application in HVDC inverters first by Bakharerski & Utevski [6], and also by Buseman [3]. The operation of this circuit may be summarized as follows:

Assuming T_1 and T_2 are conducting and T_3 is required to take over from T_1, T_7 is first fired. The capacitor has previously been charged in the direction shown, and thus T_7 goes into conduction, thereby applying the capacitor voltage across T_1 and the transformer inductance. Assuming the charge on C to be sufficient for turning off T_1, T_1 is turned off, and T_2 and T_7 continue conduction and charge C in the opposite direction. When C is sufficiently charged, T_3 is pulsed to take over from T_7, and hence the current transfer from T_1 to T_3 is accomplished. The same happens for all other transfers.

The obvious drawback of this circuit is the extra number of thyristors (over a naturally commutated bridge), high stresses (both voltage and dV/dt), because the capacitor has to be charged from full positive to full reversed voltage in a short time. A delta connected transformer winding is also a must to eliminate the inevitable 3^{rd} harmonic.

1.4.2 Forced Commutation in 1 Step [3]

This circuit is shown in Fig. 1.4.2. The capacitor is current charged as before, and each valve conducts for 60° at a time. The conduction pairs of thyristors are (4,3'), (4',5), (6,5'), (6',1), (2,1'),

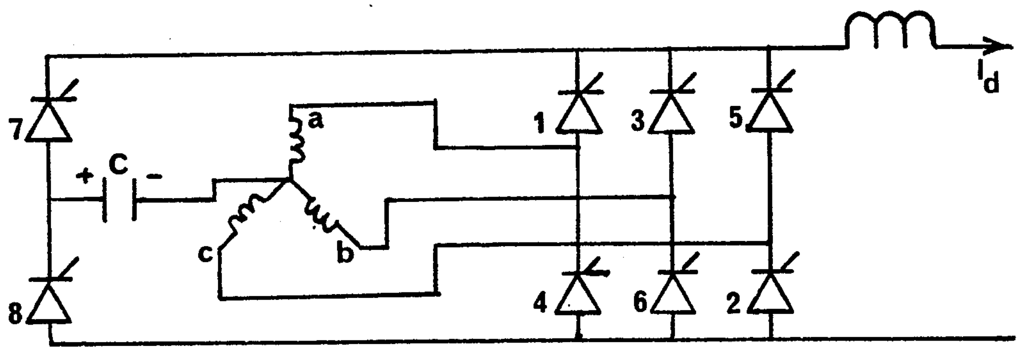


FIG 1.4.1: FORCED COMMUTATION IN 2 STEPS

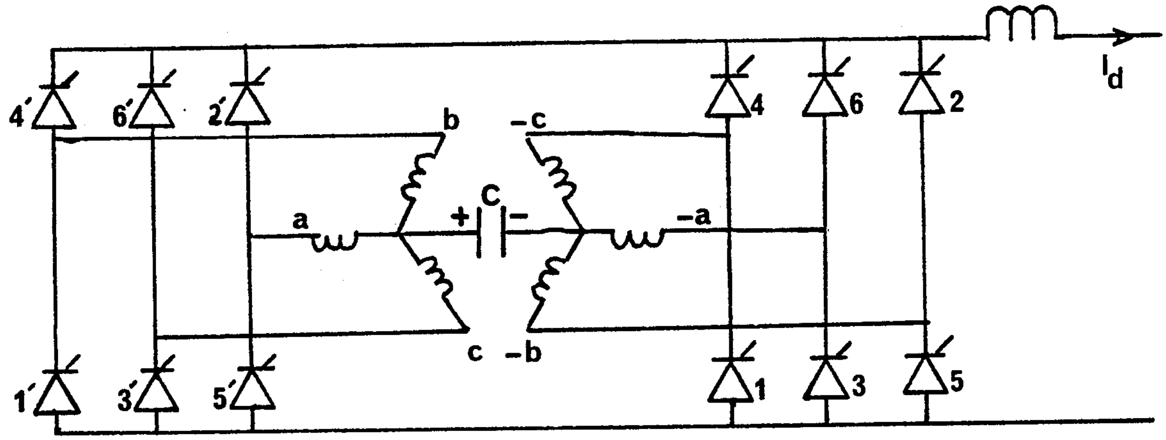


FIG 1.4.2 : FORCED COMMUTATION IN 1 STEP

(2',3) and so on in cyclic order. Consider the case when T_1' and T_2 are conducting and T_2', T_3 are to take over. Capacitor C has already been charged in a direction to forward bias T_2' and T_3. Thus, when T_2' and T_3 are pulsed, they conduct, and the capacitor voltage comes across T_1' and T_2 as a reverse bias. Thus T_1' and T_2 are extinguished.

This circuit, unlike the two stage commutated one, has the capacitor charging over a 60° interval, and thus stresses are reduced. However, the number of thyristors is twice that of a normal 3-phase Graetz bridge, and of comparable voltage and peak current ratings. Thus, the thyristor valves are underutilized.

1.4.3 Resonant Commutation [6,7]

In this method, a harmonic voltage of suitable phase angle is superposed on the fundamental voltage. This causes a delay in the zero crossover of the voltage, and hence it is possible to operate at near-unity power factors. This scheme however, requires larger smoothing reactors, than the corresponding natural commutation scheme. The resonant circuit's cost is comparable with the cost of capacitors required for static VAR supply for a normal inverter. The peak voltage value is also increased thereby causing valve stresses. Automatic tuning on the filters to compensate for slight supply frequency variations is also necessary.

1.4.4 Artificial Commutation through Voltage Injection

Gilsig and Freris [9] have discussed a scheme in which voltage pulses are injected in series with the source to suitably control the voltage during commutation. This scheme, as pointed out by the authors themselves, is of no practical value. They carried out the analysis only to gain a better understanding of the commutation process.

1.4.5 The Series Commutated Inverter

This scheme, as pointed out by Buseman [3] is the most promising one, and is discussed in greater detail in the following section.

1.5 The Series Capacitor Commutated Inverter

This inverter is similar to an ordinary 3-phase Graetz Bridge, except for the series capacitors in each phase (as in Fig. 1.5.1). It has been shown [3,5] that this scheme is competitive with a naturally commutated inverter with static capacitors for VAR generation.

Its operation is now described with reference to Fig. 1.5.1. The dc current I_d is assumed constant (a reasonable assumption on account of the high inductance in the dc circuit). The firing sequence is the same as in a normal $3 - \phi$ bridge. The firing angle (α) now may be greater than 180°. Consider the instant when T_3 is to take over from T_1, when T_1 and T_2 are on and thus phases a and c are in conduction. The following events now take place:

1. The capacitors in phases a and c charge with the polarity shown.
2. When T_3 is fired to take over from T_1, the voltages on capacitors C_a, C_b are of the correct polarity for commutation. (Capacitor C_b has been charged to the proper voltage when T_6 was in conduction before T_2 took over.)
3. After the commutation is completed, T_3 and T_2 conduct, with the voltage on C_b decreasing and on C_c increasing with the constant current flowing through them. Thus the capacitors are charged to the voltages necessary for future commutations.

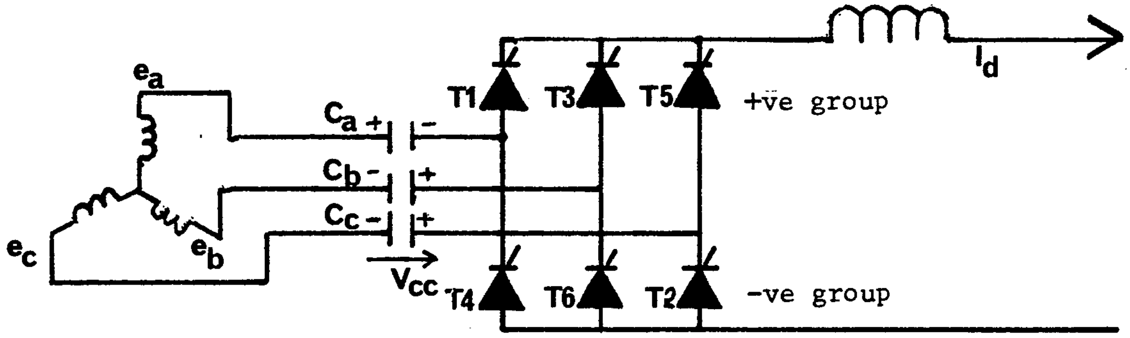
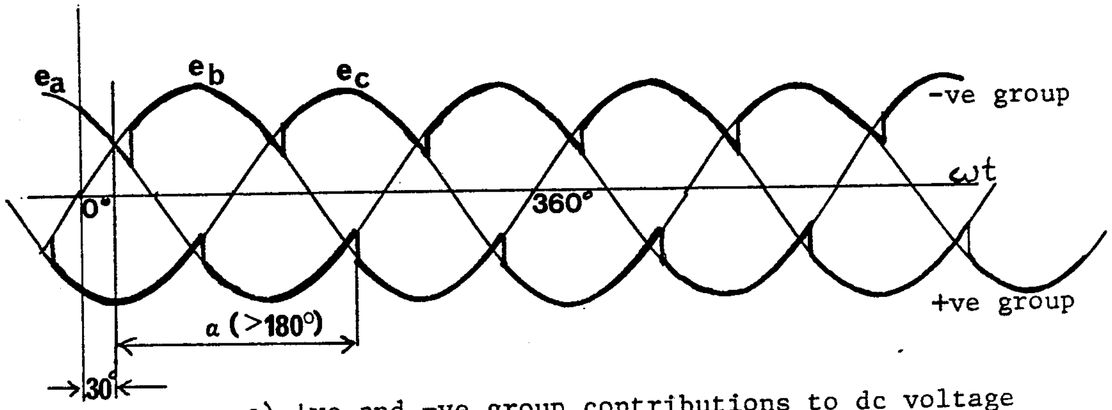
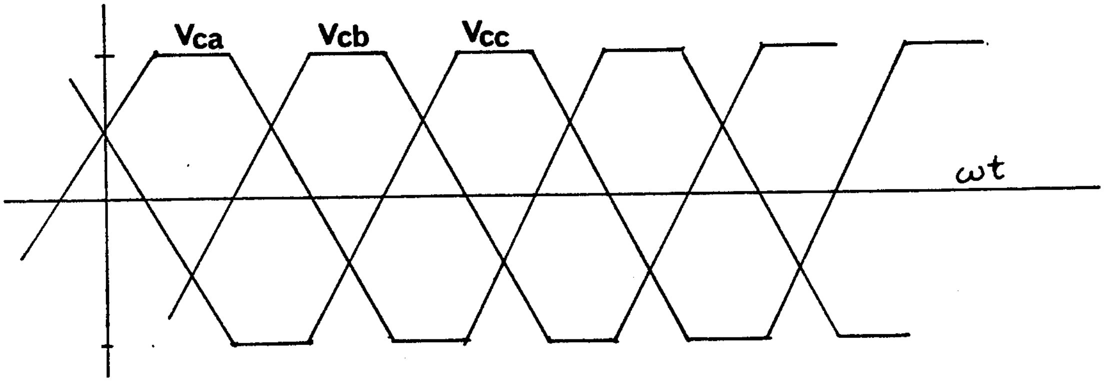


FIG 1.5.1: BASIC SERIES CAPACITOR COMMUTATED BRIDGE



a) +ve and -ve group contributions to dc voltage



b) Capacitor Voltages

FIG 1.5.2 : CONVERTER WAVEFORMS.
(TRANSFORMER REACTANCE NEGLECTED)

It is to be noted that it is the capacitor voltages (and not the line voltages) that essentially provide the commutation voltage, and so firing angles beyond 180° are possible. In this case, the line-to-line voltage subtracts from the sum of the capacitor voltages to give the net commutation voltage. Note that as the capacitors do not add any net dc voltage, the output dc voltage is essentially the same as that of a naturally commutated inverter firing at the same angle α. The resultant waveforms (ideal) are shown in Fig. 1.5.2 (a & b).

1.5.1 Reasons for selection of this circuit

Making certain assumptions about the relative costs, Buseman [3] has shown that this circuit is competetive with a naturally commutated system with static VAR supply, especially when operating at near unity power factors.

A preliminary glance at this method of commutation seems to indicate the following advantages.

i) The capacitor is current charged; and current, not voltage is the more or less constant quantity in dc systems. A voltage based forced commutation scheme (as used in ac machine control) would be prone to commutation failure as the commutation capacitors might not get charged to the proper voltages. Furthermore, a larger dc current requires a larger commutation voltage, and this happens automatically because the voltage on the capacitor is proportional to the current which charges it.

ii) No extra valves are required above the number required in a naturally commutated bridge.

iii) No special controls are required for steady-state operation other than those used in a normal 3-phase bridge.

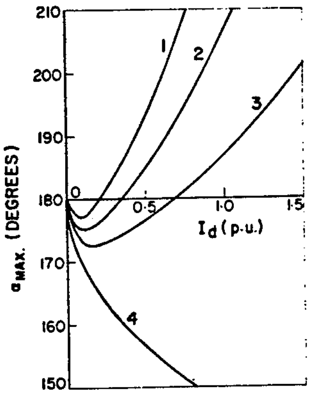
iv) Insulation coordination appears to be easy, due to the proximity of the transformer windings to the capacitors.

v) AC side harmonics, and dc side average voltage are almost the same as those in an ordinary Graetz bridge.

1.5.2 Previous work on this circuit

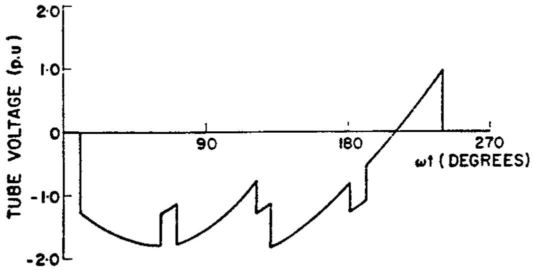
Apart from Buseman [3] mentioned earlier, J. Baron, J. Reeves and G.A. Hanley [5,8] have carried out some detailed investigations of the circuit's operation. They have covered the following aspects:

1. Detailed steady-state analysis of the bridge's operation.
2. Development of a hybrid p.u. system for analysis of a combined ac-dc system. They choose the dc current and ac side voltage as the base quantities. In conversion to actual system quantities, the $\sqrt{6}/\pi$ ac current/dc current approximation is used, *i.e.*, for 1 p.u. dc current, the ac current fundamental has a magnitude $\sqrt{6}/\pi$ p.u.
3. Ranges of operation (Fig. 1.5.3a). As the commutation voltage available is a function of current, and the success/failure of commutation a function of this voltage and the current, the maximum firing angle permissible is a function of the dc current.
4. Valve voltages and their peak values. (Fig. 1.5.3b and c). The ratings of equipment depend on the peak voltage they are supposed to withstand.
5. DC output voltages and powers. (Fig. 1.5.3d, and e).
6. Fault conditions such as commutation failure (Fig. 1.5.3f). The effect of commutation failure is more severe than in the case of a normal 3-phase bridge. In fact, the capacitors may sometimes not regain proper charge for successful commutation, and thus natural recovery may sometimes not be possible.



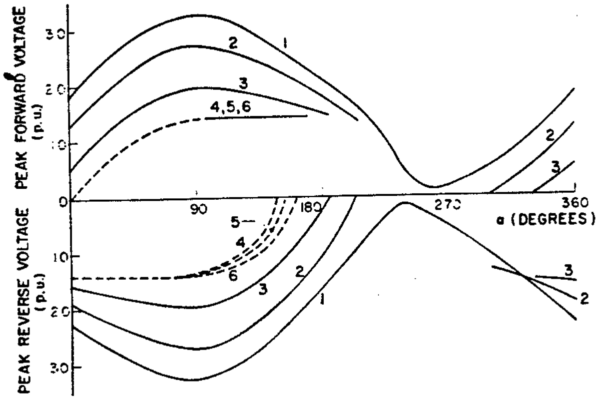
V_L = 1.0 per unit X_L = 0.111 per unit
Curve 1—X_c = 0.9 per unit
Curve 2—X_c = 0.7 per unit
Curve 3—X_c = 0.5 per unit
Curve 4—X_c = 0 per unit, natural

a) α_{max} as a function of I_d.



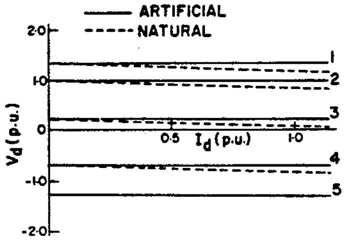
V_L = 1.0 per unit I_d = 1.0 per unit
X_L = 0.111 per unit X_c = 0.5 per unit
ωt = 0 at start of commutation $\alpha = 0°$

b) Typical tube voltage waveform (computed).



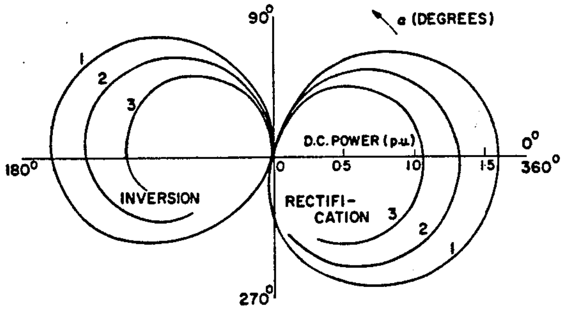
V_L = 1.0 per unit X_L = 0.111 per unit
X_c = 0.9 per unit
I_d = 1.0 per unit: 1—artificial, 4—natural
I_d = 0.7 per unit: 2—artificial, 5—natural
I_d = 0.3 per unit: 3—artificial, 6—natural

c) Peak tube voltages.



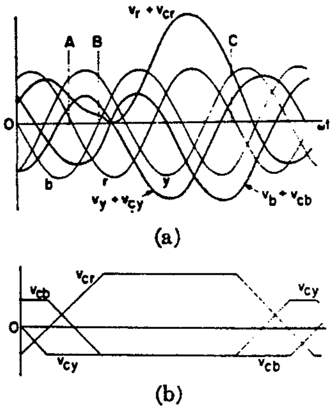
V_L = 1.0 per unit X_c = 0.7 per unit
Curve 1—α = 0°
Curve 2—α = 40°
Curve 3—α = 80°
Curve 4—α = 120°
Curve 5—α = 160°

d) Variation of V_d with I_d.



V_L = 1.0 per unit X_L = 0.111 per unit
X_c = 0.9 per unit
Curve 1—I_d = 1.2 per unit
Curve 2—I_d = 1.0 per unit
Curve 3—I_d = 0.8 per unit

e) Power characteristics.



f) Commutation failure of tube 6. (a) Phase-to-neutral and composite waveforms. (b) Capacitor voltage waveforms.

FIG 1.5.3 : CERTAIN RESULTS DUE TO BARON,REEVES AND HANLEY (5)

7. Analysis of faults such as arcbacks. (The problem of arcback is no longer important with solid-state devices.)
8. A simplified demonstration that inversion into purely resistive loads is possible with this type of inverter.
9. An outline of certain control requirements and possible strategies. They point out that techniques in which extinction angles are directly obtained should be used for determining the exact firing angle, rather than analog predictive techniques (which compute the extinction angle by feeding voltage/current information to an analog circuit). This is because of the uncertainty of the capacitor voltages which may vary during transients. Also pointed out is the possibility of using naturally and artifically commutated bridges in parallel so that a broader range of dc currents may be handled without unduly increasing the valve ratings.

1.6 Outline of the Thesis

As pointed out in the preceding sections, the series capacitor commutated inverter seems to be the best suited for HVDC applications and hence, it was felt that it deserved further study.

This thesis aims to extend the work of Baron et al to a more complete technical assessment. Thus in the course of this investigation, the following have been performed:

1. Development of a more detailed computer model for steady-state as well as transient studies.
2. Effect of ac side faults on converter operation.
3. Analysis of ac and dc side harmonics.
4. Determining the maximum rate of change of firing angle. The requirement of proper commutation voltage on capacitors dictates that

the firing angle may not be suddenly changed, as may be necessary during faults.

5. Operation into weak systems and a study of start-up.

The results indicate that the inverter is practically immune to ac side faults, that the firing angle can be changed quite fast, and that the inverter is particularly suitable for inversion into weak ac systems.

The next chapter discusses the analytical aspects of the problem and derives the necessary program flow charts. Chapter 3 discusses the results obtained for fault studies, and analysis of the rate of change of firing angle and harmonics. Chapter 4 concerns itself with inversion into weak ac systems. Finally, conclusions and recommendations are stated in Chapter 5.

CHAPTER 2

CIRCUIT ANALYSIS AND PROGRAM DEVELOPMENT

2.1 Introduction

This chapter describes how the programs used in the investigation were developed. The basic simulation routine is described first, and later sections show how other studies were incorporated into the simulation program. This chapter basically concerns itself with inversion into strong ac systems. A study of inversion into weak systems is presented in Chapter 4. The problems discussed here are:

1. Effect of ac side faults on operation.
2. Ac and dc side harmonics.
3. Determination of the maximum rate of change of firing angle.

Only the methodology is presented. Results are discussed in the next chapter.

2.2 The Basic Model

The following assumptions have been made:

1. Assumption of constancy of dc current (at least in the short run), because the high inductance in the dc circuit does not allow a high rate of change of current.
2. Neglect of snubber circuits and the possible effects of other overvoltage protection equipment on the converter.

These assumptions have been made because this study is meant to be indicative, and not a highly detailed one.