

THE UNIVERSITY OF MANITOBA

THE APPLICATION OF FORCED COMMUTATION  
FOR  
HVDC POWER TRANSMISSION

by

Hilmi Mehmet TURANLI

A thesis  
presented to the University of Manitoba  
in partial fulfillment of the  
requirements for the degree of  
Doctor of Philosophy  
in  
Department of Electrical Engineering

Winnipeg, Manitoba, 1984

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## ABSTRACT

Previous researchers have analysed the forced commutated inverters applicable for HVDC transmission and have concluded that it can be used to meet the reactive power at the inverter terminals. This investigation is a further technical appraisal involving dc links with forced commutated inverters.

Four forced commutation schemes suitable for HVDC transmission, namely Forced Commutation in Two Steps, Forced Commutation in One Step, Series Capacitor Commutated Inverter, and Forced Commutation with Dc Chopper Circuit, are investigated. It is assumed that they invert into a strong ac system. The description and modelling of each circuit including the related result are presented. Inserting the capacitors in series between the transformer secondary and the valve group known as "Series Capacitor Commutation Circuit" is considered the most promising of all the other circuits applicable to HVDC projects as a result of the above studies and by various authors. Therefore further studies are basically focused on the series capacitor scheme. For this purpose, a digital electromagnetic transients program, EMTDC, which was developed at Manitoba Hydro is used to observe the performance and operation of the circuit more precisely.

A point to point dc link which includes a forced commutated inverter at the receiving end is studied. The system is based on Manitoba Hydro's Bipole 1 System. It is shown that the forced commutated inverter can successfully operate into an extremely weak ac system and can even supply reactive power to the receiving end ac system. The economical assessment of the forced commutated inverter is examined on a comparison basis with existing HVDC systems.

Next, the performance of the series capacitor commutated inverter supplying a remote load which has no generation of its own is investigated. The system used for these studies is based on a dc link proposed to supply the town of Churchill in the northern part of the province of Manitoba from Manitoba Hydro's Nelson River Collector System having a dedicated rectifier. Various configurations are given for different procedures of starting the system up and controlling the ac voltage. It is demonstrated that the inverter which consists of two six-pulse bridges in series can work successfully even during the ac system faults. The voltage at the load bus-bar is controlled by the inverter itself, hence eliminating a telecommunication link between the rectifier and inverter terminals.

Finally, a forced commutated inverter for tapping energy to a remote load from a dc line running through a rural area is studied.

## ACKNOWLEDGEMENTS

Professor R.W. Menzies, the author's thesis supervisor, provided many useful suggestions and valuable discussions for which the author is in great debt.

The author is grateful to the Manitoba Hydro Research Committee for financial support of this project. He also wishes to thank to Mr. D.A. Woodford of Manitoba Hydro for his cooperation on the modelling and simulation aspects, and the staff of the Transmission Planning Department (System Planning Division), Manitoba Hydro where the bulk of this work was carried out.

The author would also like to thank Professor M.Z. Tar-nawecky for his helpful suggestions, and for providing his literature and reference collection.

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## LIST OF SYMBOLS

Some of the most frequently occurring abbreviations and symbols used in the text are tabulated below. Other symbols, occurring at one place only, are explained where used. (Special care has been given to use abbreviations and symbols recommended by IEEE where it exists.)

<u>Symbol</u>	<u>Representation</u>
C	capacitor
C.C.	constant current
C.E.A.	constant extinction angle
$e_p$	peak voltage
f	frequency (Hz)
G	gain
HP	high pass
Hz	hertz, cycle per second
HVDC	high voltage direct current
$I_{RMS}$	ac rms current
$I_d$	direct current
L	inductance
$L_d$	smoothing reactor
LC	inductance-capacitance
min	minimum
max	maximum
P	real power

$P_d$	dc power transmitted
P.I.V.	peak inverse voltage
pu	per unit
Q	reactive power
R	resistance
RC	resistance-capacitance
S	apparent power (MVA)
$S_i$	switch number i
S.C.C.	short circuit capacity
S.C.R.	short circuit ratio
t	time
T	period, length of period
T	time constant
$T_i$	main valve number i
$T_{ci}$	auxiliary valve number i
u	overlap period
$V_c$	capacitor voltage
$V_d$	average direct voltage
$V_{out}$	output voltage
$V_{do}$	ideal no-load direct voltage
$V_{LL}$	line to line ac rms voltage
vs	versus
$X_c$	reactance
$X_L$	capacitive reactance
X	transformer impedance
Z	impedance
$\alpha$	ignition delay angle

$\gamma$	extinction advance angle
$\phi$	phase shift
$\delta$	de-ionization time
$\Delta$	delta (transformer)
$\Delta$	a small change in ...
$\Delta$	delta, firing angle difference
$\omega$	radian frequency
$\omega_0$	natural frequency

Chapter I  
INTRODUCTION

1.1 A BRIEF COMPARISON BETWEEN NATURAL AND FORCED  
COMMUTATION

A semiconductor valve is a device which requires the current through it to be brought to zero and a reverse voltage applied across it for certain period time in order to turn it off from the conduction state. When reverse voltage is applied across the valve, it cannot conduct in the reverse direction. Instead, the voltage across the valve becomes negative. This voltage must remain negative long enough for adequate deionization. Once the valve is deionized, the valve remains blocked even if it is forward biased until a gate pulse is applied. The transfer of current from one valve into another, called commutation, is usually provided by the ac line voltage itself in case of a conventional HVDC converter. As an alternative, the required reverse voltage can be supplied in some other way (usually by capacitors which are initially charged to proper voltage by means of an auxiliary circuit), the method being called "artificial" or "forced" commutation.

A detailed analysis concerning the comparison of different converter circuits [1] shows the superiority of the

three phase bridge circuit also known as Graetz Bridge for use in HVDC power transmission. The schematic circuit of the bridge is given in Fig.1.1 the valves being numbered according to their firing sequence.

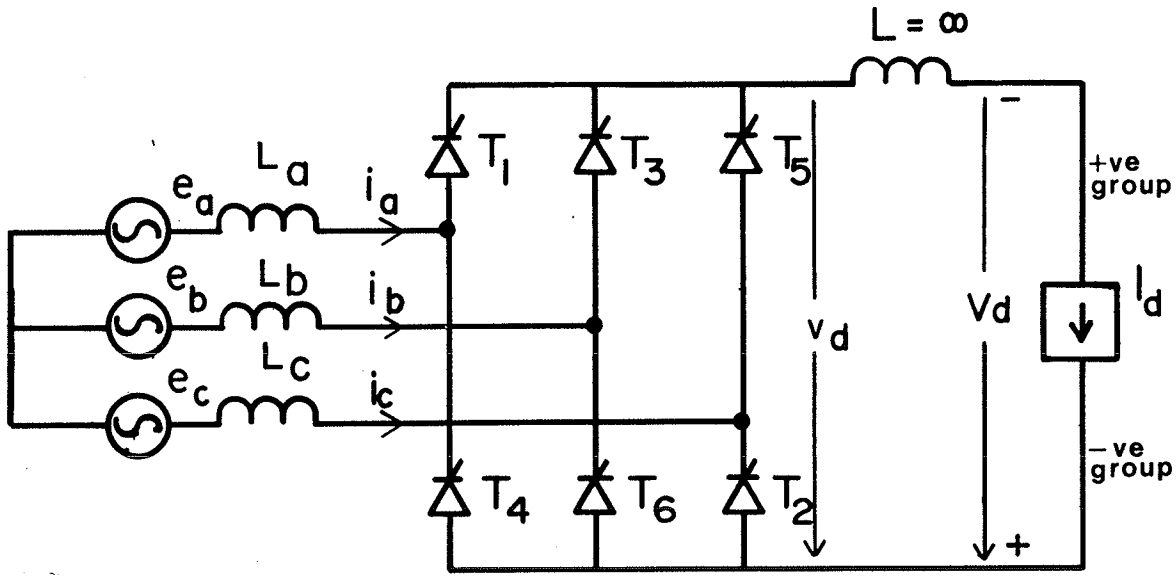


Figure 1.1: Schematic diagram of the three phase bridge circuit

For a diode bridge the in-coming valve will turn on as soon as the voltage across it is slightly positive. If the ac source does not have any inductance, commutation occurs instantly. Therefore, the rectangular pulses of alternating line current are centered under the positive and negative cycles of the line to neutral voltage (Fig.1.2). For a controlled bridge, the ignition of a valve can be delayed for an angle  $\alpha$ , called the delay angle. The valves are triggered according to their sequence i.e.  $i = 1, 2, 3, 4, 5, 6$

each after  $60^\circ$ . The delay angle is measured from the natural commutation point at which the forward voltage just starts to appear across the incoming valve. Therefore, the ignition delay creates a phase shift of angle  $\phi = \alpha$  between the fundamental component of the current and the voltage (Fig.1.2-b). For natural or line commutation the delay angle is restricted to the range  $0^\circ$  to  $180^\circ$ , theoretically. As a result, the converter, as either rectifier or inverter draws reactive power from the ac system. The rectifier is considered to be taking lagging current from the ac system and the inverter is considered either taking lagging current or supplying leading current to the ac system.

For rectifier operation, the delay angle  $\alpha$  can be set quite small and the system can be operated close to unity power factor, thus consuming less reactive power since there is no danger of voltage reversal before completing the commutation. But if a number of thyristors are used in series to construct a bridge arm, it may not be possible to reduce the delay angle less than 5 degrees in order to ensure all the thyristors in the arm are forward biased. Also, it is always recommended to keep the delay angle around 10 to 20 degrees for a compromise of keeping the power factor high and having a margin for quick increases in rectifier voltage.

For inverter operation, the fundamental component of current lags the ac voltage waveform by a phase angle

$$\phi = 180^\circ - \alpha$$

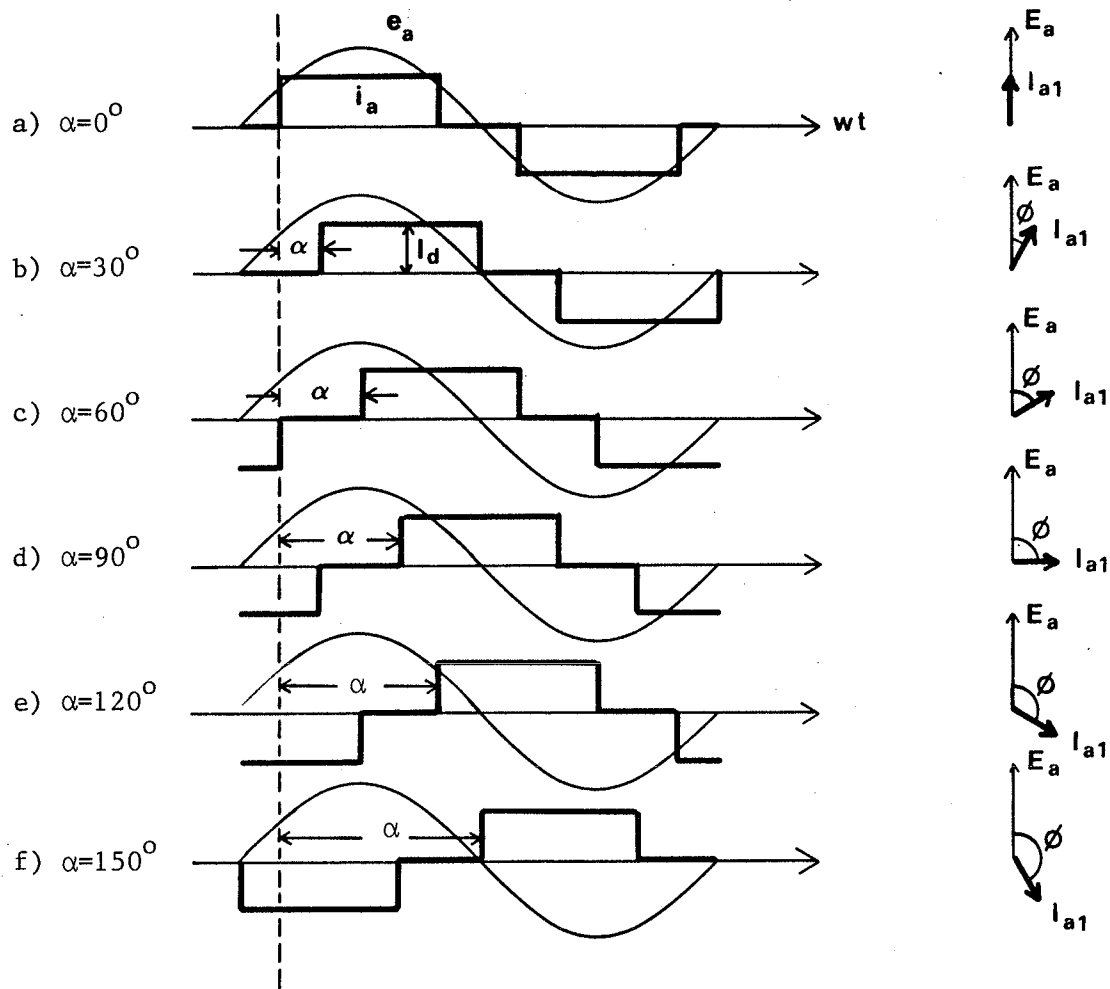


Figure 1.2: Relation between firing angle and phase displacement for a naturally commutated converter [1].

as it is seen from Fig.1.3 neglecting the overlap angle. It is not possible to increase the delay angle close to  $180^\circ$  or beyond it, because the reverse voltage to turn-off the device should be present for certain period of time, referred to as deionization time or extinction angle, across the valve. Also, because of the impedance of the converter transformer and the ac system, the transfer of current from

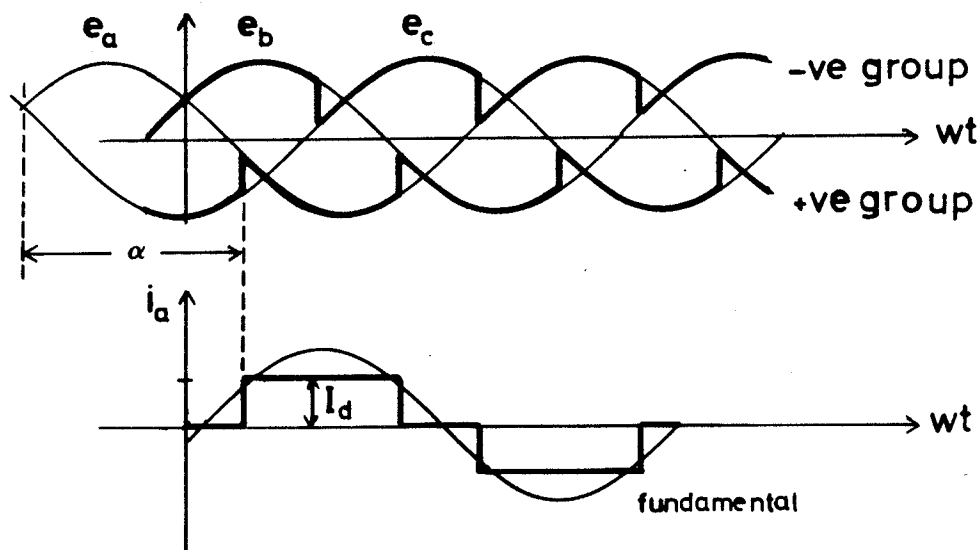


Figure 1.3: Output voltage and ac current waveforms (overlap ignored)

the phase of the out-going valve into the phase of the incoming valve takes some time called overlap duration, denoted by angle  $u$ . The overlap duration is about 20 to 25 degrees for typical full load values depending upon the commutating reactance and the delay angle. Deionization time,  $\delta$ , should be greater than the turn-off time of the valve (about 100-200  $\mu$ s typically). Thus the maximum delay angle at which the bridge may be operated is given by the equation

$$\alpha = 180^\circ - \delta - u$$

and the delay angle  $\alpha$  can be increased only to  $135^\circ$ - $140^\circ$ . Since the fundamental current is lagging the ac source voltage, the inverter will consume reactive power. For a naturally commutated inverter the requirement of reactive power reaches values of 60 % of the real power depending upon the

extinction angle at which the system is operating. The reactive power required by the inverter must be supplied by the ac commutating busbar of the inverter from generators working in the ac system, synchronous condensers or static capacitors.

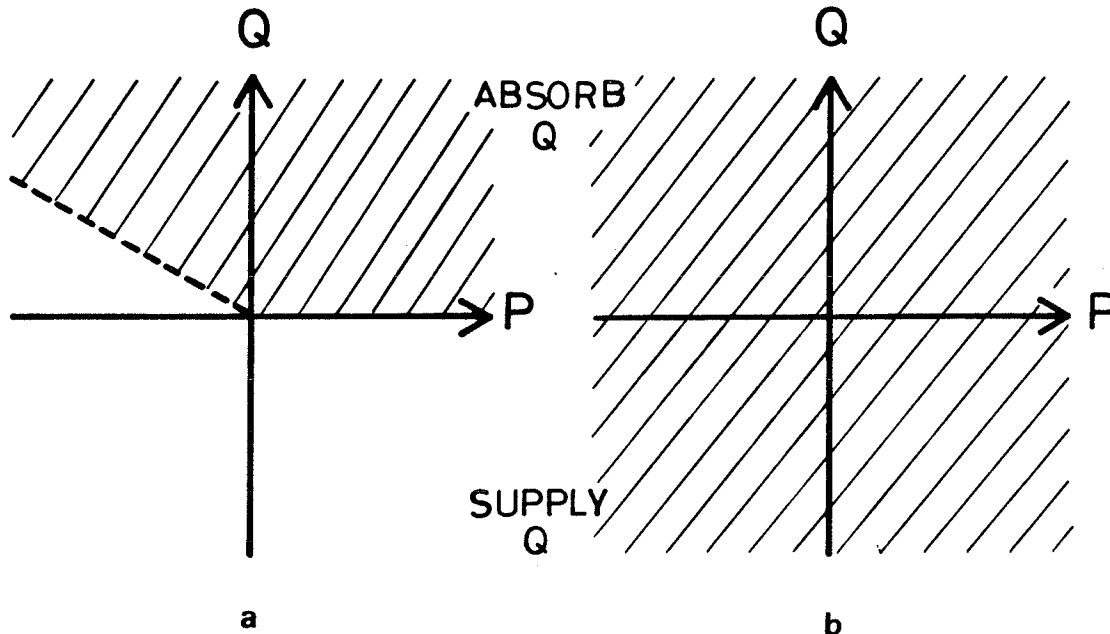


Figure 1.4: Ranges of operation of a converter  
 a - Natural commutation,  
 b - Forced commutation.

The range of operation for a converter is shown in Fig.1.4. For the case of natural commutation, it is not possible to operate the inverter so that it consumes no reactive power because of extinction angle limitation. However, in forced commutation, artificial devices are used to maintain a reverse bias voltage across the out-going valve

even after the line voltage is reversed. The voltage reversal point across the device is shifted beyond the natural commutation instant. This gives the possibility of increasing the firing angle to angles which are unattainable in natural commutation. There is even the possibility of supplying reactive power into the ac system by operating the inverter at a delay angle beyond  $180^\circ$ . Fig.1.5 shows the phase displacement between voltage and current phasors of a forced commutated converter. As seen from the figure as the delay angle becomes greater than  $180^\circ$ , current starts leading the voltage. Since the reactive power consumption of the inverter is eliminated, there is no need to have a strong reactive power source at the ac commutating busbar. In fact, as it is shown in Fig.1.4-b, ideally it might be even possible to operate the converter in all four quadrants. By means of controlling the reactive power consumed / produced by the inverter, it is possible to control the voltage very quickly at the commutating busbar of the inverter.

Another advantage of the forced commutation is that since it produces its own commutating voltage, there is no need for an existing ac source at the receiving end system. Hence inversion can take place successfully even into dead systems; that is, systems without any generation or rotating machines.

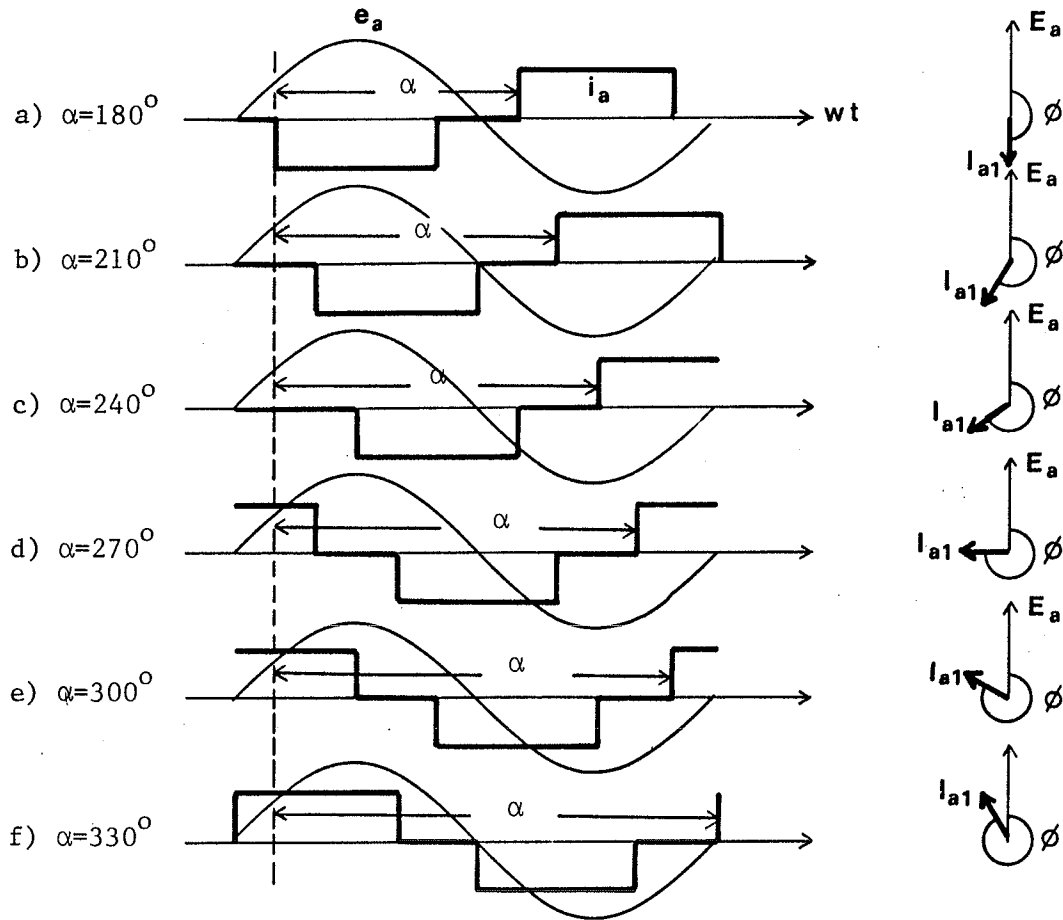


Figure 1.5: Relation between firing angle and phase displacement for a forced commutated converter

## 1.2 THE NEED FOR FORCED COMMUTATION

The supplying of reactive power into the naturally commutated inverter requires a relatively strong ac system for successful commutations. For a forced commutated inverter, the reactive power requirement is supplied by the inverter itself, thus there is no need for a strong system. The introduction of a forced commutated inverter might increase the number of applications in which dc transmission might be

superior to ac transmission. With a forced commutated inverter, it is possible to invert into weak and even dead ac systems. A solid state, self contained tap on an HVDC line may operate successfully, hence removing the problems such as inherent maintenance of synchronous and diesel machines.

Whether such methods of forced commutation are preferred over the naturally commutated inverter or not depends on the relative cost of the inverter to that of conventional means of reactive volt-ampere generation on the ac inverter busbar.

### 1.3 REQUIREMENTS OF FORCED COMMUTATION SCHEME

Irrespective of the scheme which might be selected as the forced commutation circuit, there are a number of requirements which should be met in order to operate the converter successfully. These requirements can be classified as :

- High reliability : It is very important to have a reliable system especially supplying a weak or dead load which has no back-up source.
- Minimal stresses on components : The voltage stresses across the converter equipment and current stresses through them should be minimized in order to reduce the cost of the converter station.
- Quick change of firing angle ( $\alpha$ ) should be possible. Fast control of  $\alpha$  provides the control of real and reactive power flows into the ac system as well as good transient and fault performance.

- Easy and fast system recovery is necessary for either a fault in the ac system or for a dc line fault.
- Wide range of operation : The converter should be able to operate over a wide range of power and current without the risk of commutation failure.
- Quick, easy and reliable start-up procedure especially for operation into a weak or dead load.

#### 1.4 AN EXAMINATION OF FORCED COMMUTATION SCHEMES

There are many ways of forced commutation in the area of low power with quite sophisticated design and control, but these inverters are designed to provide a wide range of frequency. HVDC inverters do not have to satisfy this requirement, but they must operate reliably at much higher voltage and current levels. There are number new developments in thyristor design, such as gate-turn-off (GTO) thyristors and power field effect transistors (FET), but their ratings are not yet applicable to HVDC valves and also they require sophisticated and high power gate pulse arrangements. Therefore the forced commutation schemes for the high power and low power area are different, and hence only schemes using standard thyristor valve arrangements will be considered. Some of the proposed HVDC forced commutation schemes which will be studied in detail are {2,3,4} :

- i) Forced commutation in two steps,
- ii) Forced commutation in one step,

- iii) Series capacitor commutated inverter,
- iv) Dc chopper commutation,
- v) Resonant commutation,
- vi) Artificial commutation through voltage injection.

#### 1.4.1 Forced Commutation in Two Steps

The configuration of this inverter is given in Fig.1.6. In addition to the normal three-phase bridge configuration, the circuit contains two auxiliary valves, a capacitor C and a delta tertiary winding.

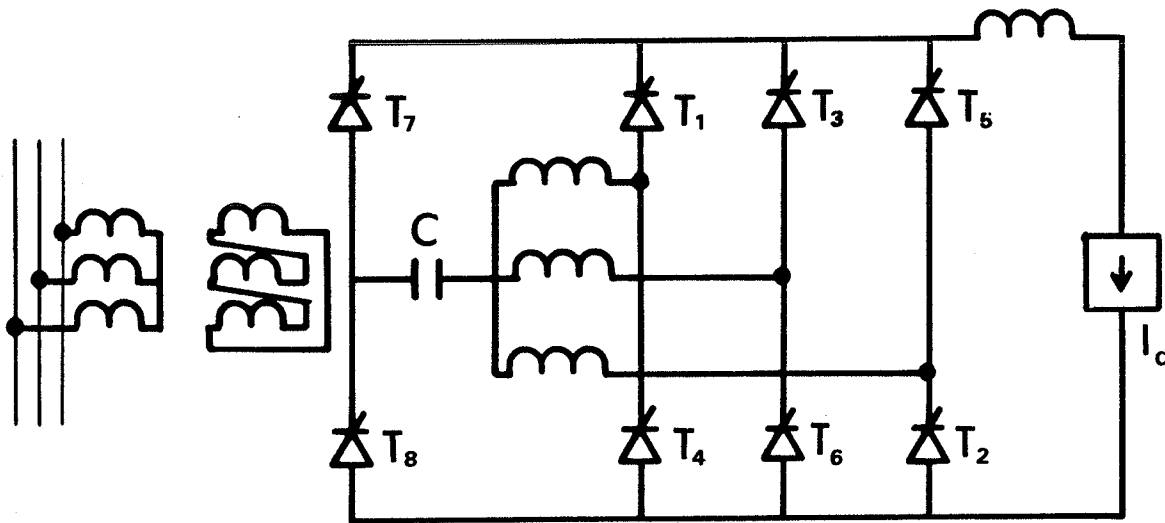


Figure 1.6: The configuration of the inverter with forced commutation in two steps

In the case of a normal three-phase bridge, the current commutates directly between the valves of one group, i.e. valves 1, 3 and 5 in the positive group. But in the circuit

given, commutation takes place to an auxiliary valve which is at much more positive voltage than the in-coming valve of the bridge. The voltage across the auxiliary valve while it is conducting is so arranged as to change its direction thus making possible the commutation of the current from the auxiliary valve to the next valve in the bridge, even at a leading power factor. The capacitor C and the auxiliary valves have to work at a frequency of three times the fundamental frequency.

#### 1.4.2 Forced Commutation in One Step

The configuration of the inverter with forced commutation in one step is given in Fig.1.7. The converter consists of two three-phase bridges connected by the capacitor between the transformer neutrals. The transformer has two star connected secondaries in phase opposition, i.e. phase voltages of each bridge are displaced by  $60^\circ$ .

Each valve conducts for  $60^\circ$  and commutation takes place in one step. During an interval of  $60^\circ$ , the current enters through one of the valves on the top left and leaves the inverter through one of the valves on the bottom right. The commutation in positive and negative groups takes place simultaneously. After commutation, the current enters one of the valves on top right and leaves through one of the valves on the bottom left.

Current flows through the capacitor continuously only changing its direction every  $60^\circ$ . Therefore the capacitor works at three times the system frequency. At the end of each  $60^\circ$  interval, the capacitor is charged in the correct polarity in order to commutate the valves.

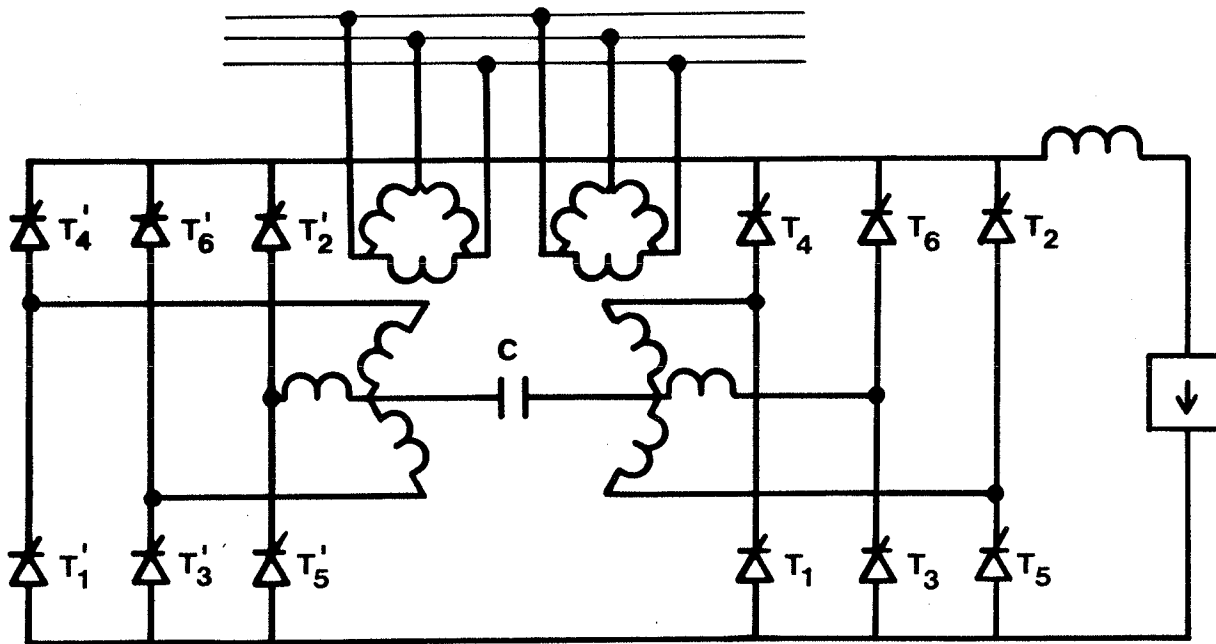


Figure 1.7: The configuration of the inverter with forced commutation in one step

#### 1.4.3 The Series Capacitor Commutated Inverter

This method is the simplest of the available methods of forced commutation. The configuration of the inverter is as shown in Fig.1.8. The capacitors can also be connected in the transformer neutral. The arrangement and the firing sequence of the converter and therefore the operation of the

circuit are exactly the same as the conventional three-phase bridge. The circuit requires no auxiliary valves. Therefore the capacitors may even be added to an existing plant provided that the valves are able to withstand the extra voltage stresses.

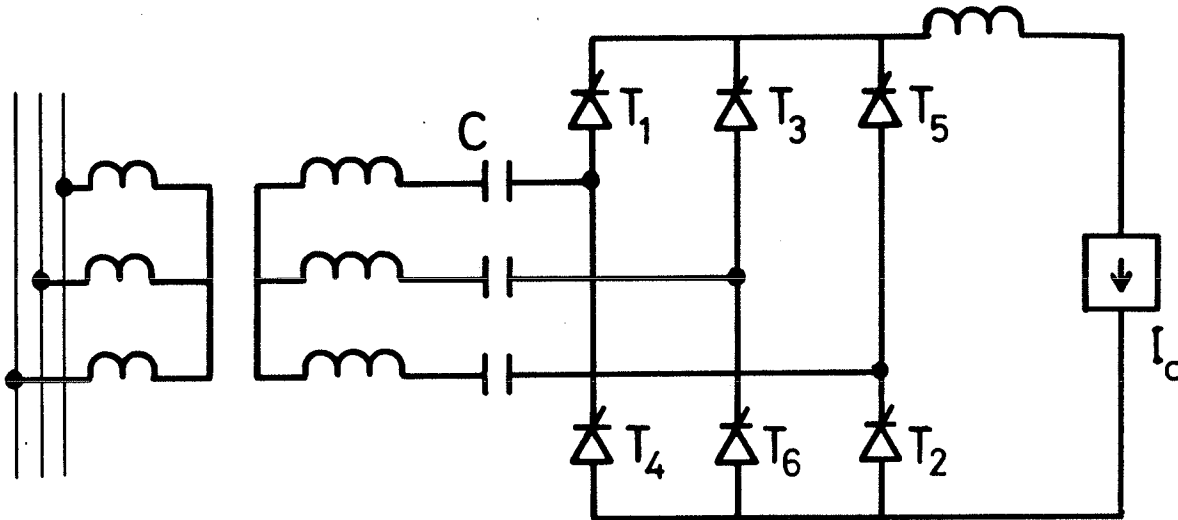


Figure 1.8: The configuration of the series capacitor commutated inverter

#### 1.4.4 Forced Commutation with Dc Chopper Circuit

The configuration of this scheme is given in Fig.1.9. This scheme was proposed as a series tap {5,6} . The circuit contains four auxiliary valves with the same ratings as in main valves and a capacitor C in addition to the normal three-phase bridge arrangement.

The operation of the circuit is quite different than the normal bridge operation. Since the dc current is defined by

the main rectifier and inverter, the tap power should be controlled by the tap itself simply by shorting the tap several times in a cycle. In case of a normal three phase bridge operation, the current commutates directly between the valves of one group. But in the dc chopper circuit, before the current is transferred to the next valve, the tap should be by-passed in order to control the power injected into the ac system. By-passing action can be performed by the main valves themselves in a cyclic order. The necessary commutation voltage to by-pass the tap is supplied by the ac system. The capacitor C provides the necessary commutation voltage to turn-on the auxiliary valves at the end of the by-pass period and to transfer the current to the incoming main valves from the auxiliary valves. The capacitor C and the auxiliary valves work at a frequency of three times the fundamental ac system frequency.

#### 1.4.5 Resonant Commutation

In this method, a particular harmonic voltage with a suitable phase-angle is superimposed on the fundamental phase voltage such that it might be possible to provide extra commutation voltage during the commutation and delay the zero crossing of the voltage across the out-going valve, therefore enabling the inverter to work around unity power factor {4} .

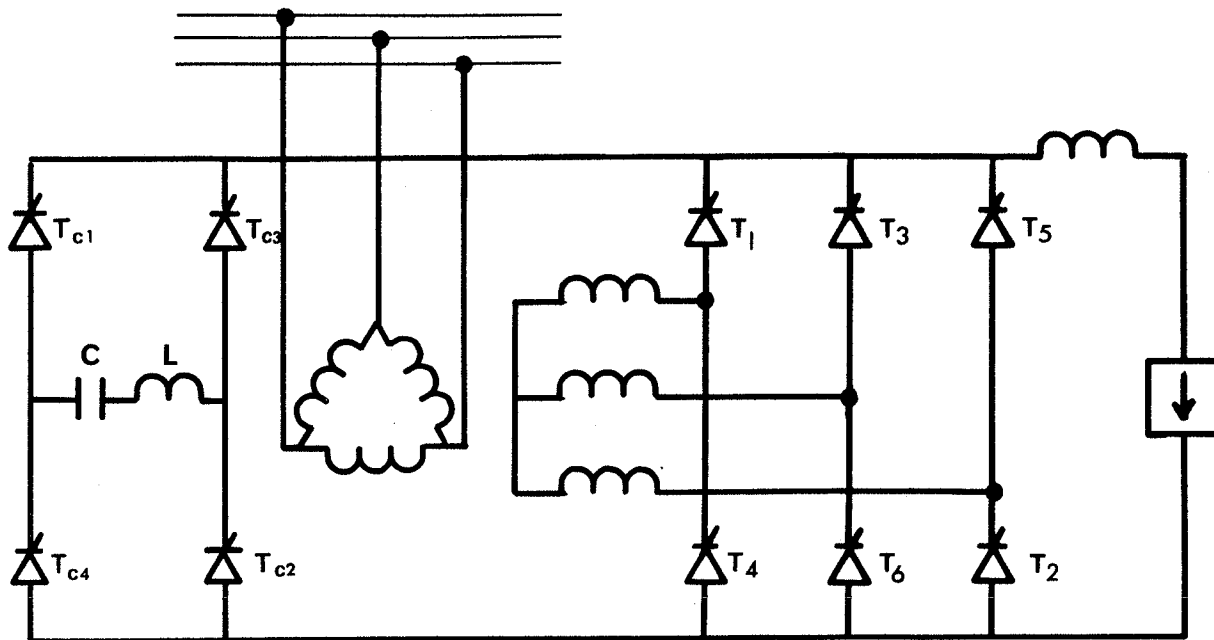


Figure 1.9: The configuration of dc chopper scheme

As it is seen on Fig.1.10, a resonant circuit is placed on each line in order to take advantage of the harmonics on the line current and generate the required harmonic voltage to be superimposed on the fundamental wave.

#### 1.4.6 Artificial Commutation Through Voltage Injection

Gilsgig and Freris [7] have proposed a circuit in which voltage pulses are injected into the source to control the voltage during commutation. But as was pointed out by the authors, this circuit has no practical value.

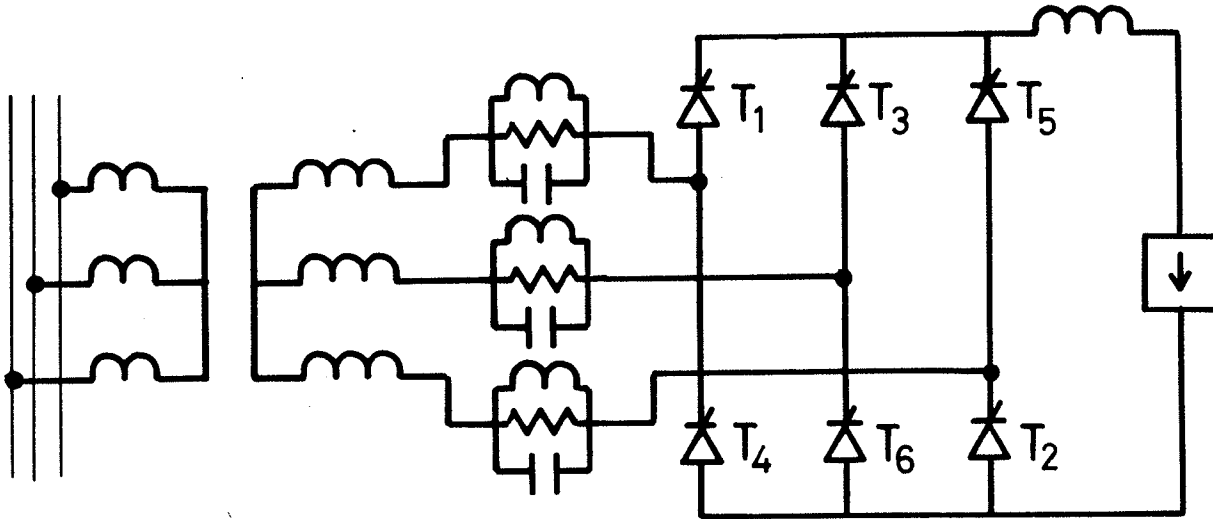


Figure 1.10: The configuration of the resonant commutation circuit

### 1.5 OUTLINE OF THE THESIS

The previous researchers have examined the individual circuits superficially {2,3,8}. For the purpose of comparison, detailed computer models for steady-state and transient studies of the first four schemes introduced in this chapter were developed. The following analyses are performed for each circuit :

- i) Effect of three-phase-to-ground and single-phase-to-ground faults on the converter operation,
- ii) Analysis of ac side current and dc side voltage harmonics,
- iii) Determination of the maximum permissible rate of change of delay angle.

The description and modelling of each circuit including the related results are presented in the next chapter. The studies start with assumptions such as a strong ac system, smooth dc current, equidistant firing and no snubber circuits. Comparison of the results of these studies indicate the technical superiority of the series capacitor commutation circuit and therefore, further studies are based on this scheme.

For subsequent studies, a digital electromagnetic transients program, MH-EMTDC, developed at Manitoba Hydro, is used to observe the performance and operation of the series capacitor scheme in a number of realistic applications.

The studies presented in Chapter III cover a point to point dc link which includes a forced commutated inverter at the receiving end. The studies are based on Manitoba Hydro's Bipole 1 System. It is shown that the forced commutated inverter can operate successfully into a relatively weak ac system and can even supply reactive power to the ac system using a delay angle beyond  $180^\circ$ . The valve stresses are examined on the "Bipole 1 System" studies and compared with the naturally commutated inverter using the thyristor information of Bipole 2.

Chapter IV describes the performance of the series capacitor commutated inverter supplying a remote load which has no generation of its own. The system used for these studies is based on a dc link which is proposed to supply the town

of Churchill in northern Manitoba from the Manitoba Hydro's Nelson River Collector System having a dedicated rectifier. Various configurations are given for different procedures of starting the system. It is demonstrated that an inverter consisting of two six-pulse bridges in series, can start-up and operate reliably. The voltage at the load bus-bar is controlled by the inverter itself hence eliminating the need for a fast telecommunication link between the rectifier and inverter.

A forced commutated inverter for tapping energy to a remote load from a dc line running through a rural area is studied and simulation results are presented in Chapter V focusing on the interaction between the main inverter and the tap systems.

Finally, conclusions and recommendations are stated in Chapter VI. The per unit system and system data used in simulation studies are presented as appendices at the end of the thesis.

## Chapter II

### A COMPARISON OF FORCED COMMUTATION SCHEMES FOR HVDC TRANSMISSION

#### 2.1 INTRODUCTION

The first four forced commutation schemes which were introduced in Chapter I are further investigated by using digital analysis techniques. The last two schemes, namely the resonant commutation and artificial commutation through voltage injection methods are not included in further studies, because as pointed out by the authors themselves, either they are quite costly or not practical for HVDC applications.

The series capacitor commutation circuit has been previously studied using Laplace Transform Method for steady-state analysis {8} and the state variable method for investigations of harmonics, faults and the rate of change of delay angle {9,10,11}. The present research has expanded the previous work to include valve stresses, rate of change of valve voltage and currents, available turn-off time of valves and overlap duration all as a function of delay angle. The selection of the commutation capacitor for various range of operation was also determined.

The other three schemes were superficially analysed {2,3,5,6}, therefore the research presented here included all of the above studies for comparison purposes. This chapter summarises the pertinent results of the studies for each scheme. The results of all of the comparison studies are included in a technical report {12}.

## 2.2 THE THEORETICAL BACKGROUND

### 2.2.1 The Solution Method

The state variable approach is used to formulate the system during the overlap periods. The number of differential equations which will be solved to obtain the response of the circuit is minimum with this method {13} . Also the set of differential or state equations is valid for both transient and steady-state solutions.

The equations describing the system are arranged in the form of

$$\dot{x}(t) = \{A\}.x(t)+\{B\}.u(t)$$

$$y(t) = \{C\}.x(t)+\{D\}.u(t)$$

where

x : the vector of state variables (capacitor voltages and inductor currents),

u : the vector of input quantities (source voltages and currents),

y : the vector of response quantities ( i.e. most device voltages and currents),

A, B, C and D are matrices describing the system.

The above differential equation is solved using Euler's Method {14} as

$$\Delta x = A x \Delta t + B u \Delta t$$

where

$\Delta x$  is the change in  $x$  over  $\Delta t$  then

$$x_{\text{new}} = x_{\text{old}} + \Delta x$$

Once the state variables are calculated, the second equation (response equation) is used to calculate most of the device voltages and currents which enables one to observe any quantity in the circuit.

Between the overlap periods simple linear equations are used to solve for the capacitor voltages and inductor currents, because of the assumption of the constant dc current. At the beginning of each overlap period the initial vector of state variables is reset, hence eliminating the possibility of numerical error accumulation.

The validity of this method was confirmed by the duplication of the steady-state results of the previous researchers. A higher order numerical solution technique, Gear's Algorithm {15}, was also used to verify the accuracy of Euler's Method.

For the purpose of this chapter only, the commutation capacitors are assumed to be charged with the appropriate voltage and polarity to handle the first commutation. No attempt has been made to investigate the start-up of the inverter.

## 2.3 THE SERIES CAPACITOR FORCED COMMUTATION SCHEME

### 2.3.1 The Circuit Diagram and the Operation of the Circuit

The circuit diagram and the firing sequence of the valves are given in Fig.s 2.1 and 2.2, respectively. Neglecting the effect of the transformer impedance, we can assume the commutations between valves will be taking place almost instantaneously. In steady state, the capacitor voltage waveform has a constant current charging for  $2\pi/3$  radians, a constant voltage period for  $\pi/3$  radians when the related phase is not conducting, and another constant current charging in the opposite direction for  $2\pi/3$  radians. Therefore the capacitor voltage has a trapezoidal waveform with zero average value. The commutating voltage consists of two components, namely, transformer voltage and capacitor voltage. The phase shift which is supplied by the superposition of the capacitor voltage on the transformer voltage with respect to ac waveform enables the firing of the valves beyond the normal operating region {8}.

The operation of the circuit is available in the literature and is only summarized here. Assuming that system is operating in steady-state with valves  $T_1$  and  $T_2$  in conduction, the following events take place :

- i) The capacitors in phases a and c charge with the polarity shown. Capacitor  $C_b$  has been charged to the required voltage when  $T_6$  was conducting before  $T_2$  took over.

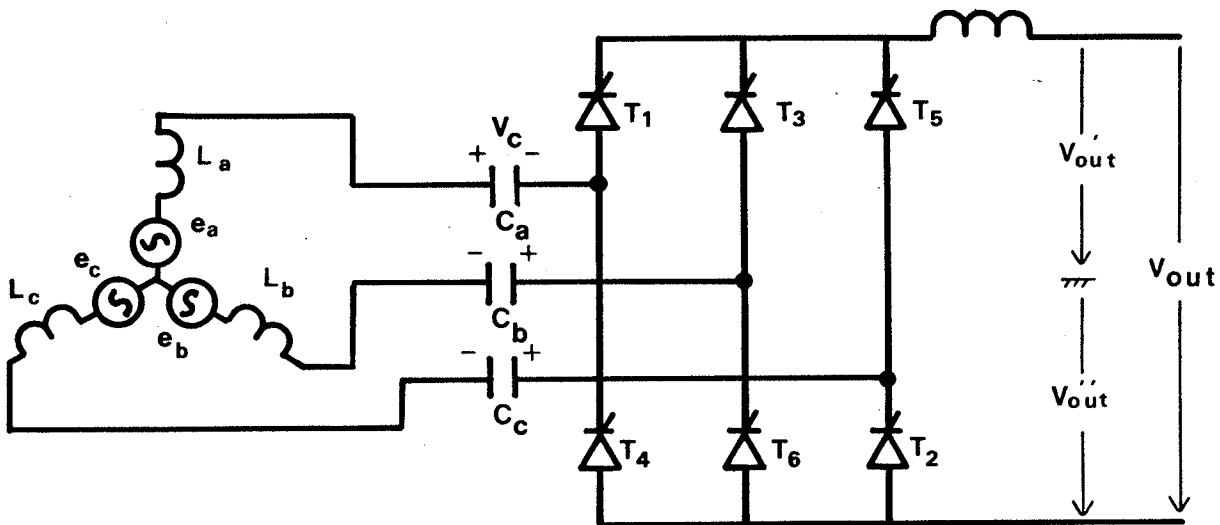


Figure 2.1: Circuit diagram of the series capacitor scheme

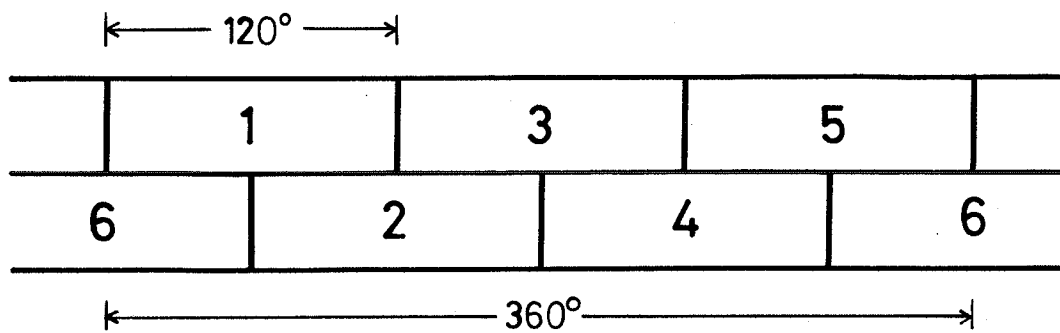


Figure 2.2: Firing sequence of the valves for series capacitor scheme

- ii) When  $T_3$  is fired to take over from  $T_1$ , the voltages on capacitors  $C_b$  and  $C_a$  are of the correct polarity for commutation.
- iii) After the commutation is completed,  $T_3$  and  $T_2$  conduct, with the voltage of  $C_b$  decreasing and of  $C_c$  increasing with the constant current flowing

through them. Thus the capacitors are charged to the voltages necessary for the next commutation.

It is to be noted that it is the capacitor voltages that essentially provide the commutation voltage and so firing angles beyond  $180^\circ$  are possible. In this case, the line-to-line voltage subtracts from the sum of the capacitor voltages to give the net commutation voltage.

### 2.3.2 Range of Operation

The range of firing angle for which the steady state operation is possible depends upon the ac supply voltage and dc current value. For a certain charging period, theoretically  $2\pi/3$  radians, as the value of the capacitor becomes smaller, the voltage accumulated across it between commutations becomes larger. The choice of capacitor relative to the rating of the system determines the maximum delay angle,  $\alpha_{\max}$ . It is possible to choose the capacitor to allow complete four quadrant operation but this is at the cost of increased voltage stresses.

### 2.3.3 Program Results and Discussion

A program was developed in order to observe the transient, and steady state performance of the series capacitor commutated inverter. Although the program assumes the same model as Reeve et al {8} used, the method of the solution used for the basic program is different than the method they

have used. As it will be seen in the next sections, most of the results are in close agreement with the same steady state solutions that Reeve obtained. The program used here has the ability also to perform a transient solution given any initial condition, fault studies and harmonic analysis.

In order to start either a transient or a steady state operation, the capacitors connected in series with phases a and b should have the appropriate charges as described in previous section to handle the first commutation. To charge the capacitors for starting the system up or for recovery from a failure, the dc line itself can be used. For a point to point system, different ways of starting the system will be described in later chapters.

Fig.2.3 shows some typical waveforms for the series capacitor commutated inverter working with a delay angle of  $180^\circ$  after reaching steady state. The overlap angle is about 0.3 ms (about 7 electrical degrees) for the parameters given in the figure. (Unless otherwise it is stated, the same set of parameters is used for all of the results presented.) In order to make the studies universally applicable, a hybrid per unit system which considers the real power as invariant on either side of the converter is used (Appendix A). The capacitors charge up to a voltage of 1.0 pu. As is seen from the figure (Fig.2.3), the maximum forward and reverse voltage across the valve which extinguishes at  $t = 0.0$  s of the waveform are 2.3 pu and 1.7 pu, respectively. Since the

output dc voltage is measured at the converter side of the smoothing reactor, it consists of ripples at six times the fundamental frequency.

Fig.2.4 shows both peak forward and reverse valve voltages at different values of the dc current for forced commutation and for natural commutation. As it is seen from the figure, peak forward and reverse voltages for the natural commutation with different values of dc current are equal. The peak voltage stresses increase as the dc current is increased since the capacitor voltages charge to greater voltage levels in forced commutation. For the impedance of the capacitor equal to 0.9 pu and unity dc current, peak forward and reverse voltages are quite reduced for the operation of the delay angle in the third quadrant. In order to reduce valve stresses when controlled power reversing is desired, different operating procedures can be employed such as {8} :

- i) The converter can be blocked temporarily and de-blocked in the rectifier region,
- ii) The capacitors can be installed in units and capacitor switching can be introduced with the increased cost of ac circuit breakers.
- iii) If the four quadrant operation is possible, the transition can be made by increasing the delay angle into the rectifier range of operation,

Since it is the capacitor voltage affecting the valve stresses, it might be possible to control the delay angle to limit the transient capacitor voltages.

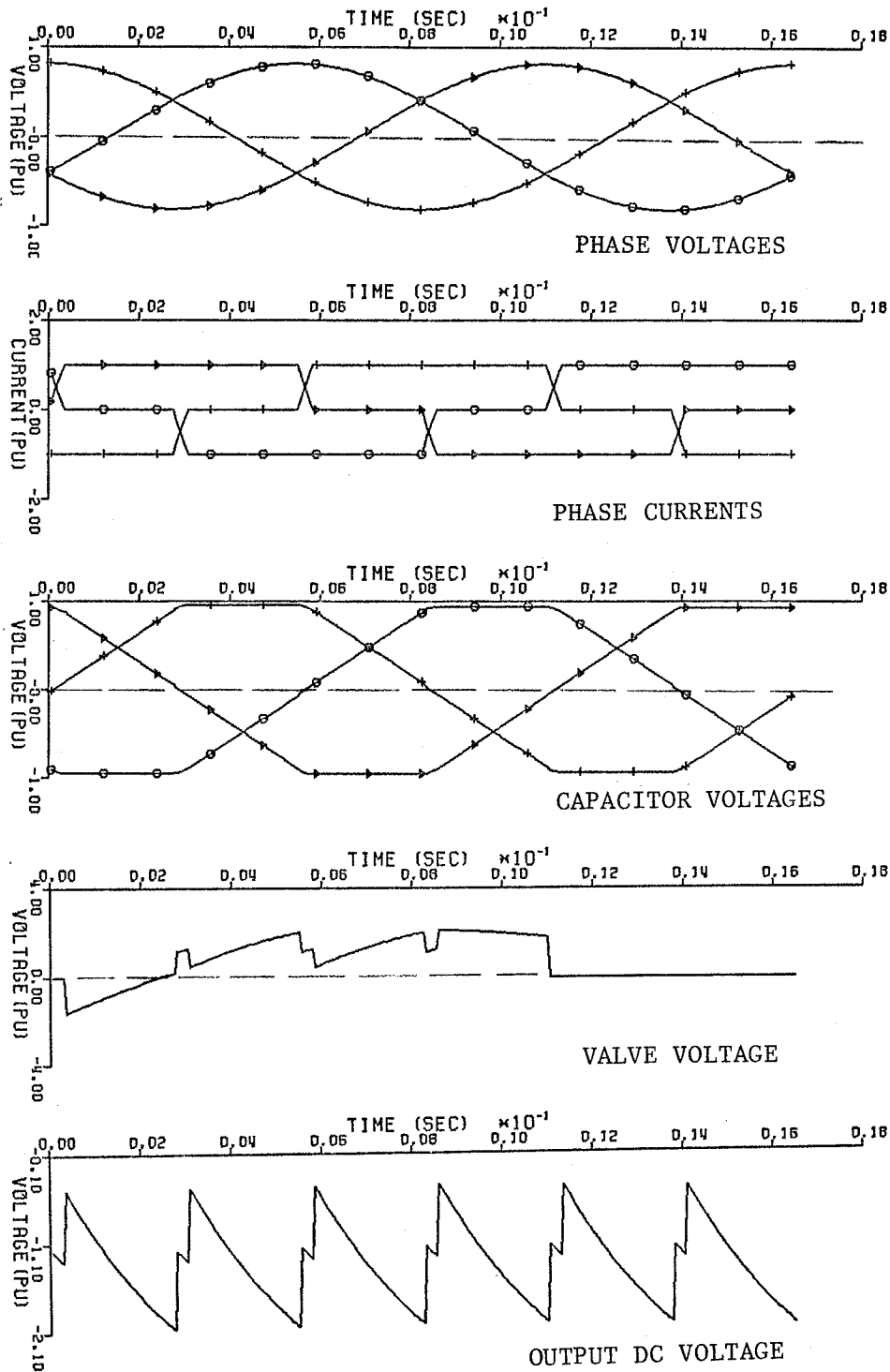


Figure 2.3: Various waveforms for series capacitor circuit  
 $e_p=0.8165$  pu ( $V_{LL}=1.0$  pu),  $X_L=0.111$  pu,  
 $I_d=1.0$  pu,  $X_C=0.9$  pu,  $\alpha = 180^\circ$

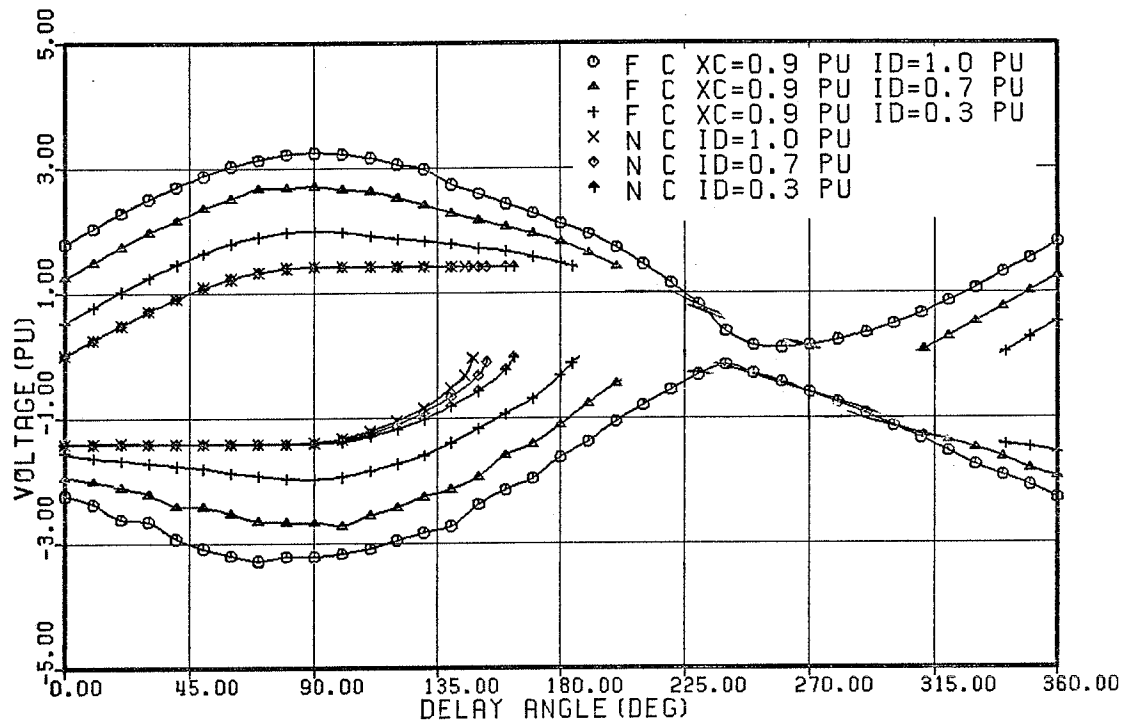


Figure 2.4: Peak valve voltages

Using the harmonics program, ac side current and dc side voltage harmonics are studied for the steady state operation. The dc output voltage is affected by the voltages across the series capacitors. Therefore in order to observe the effects of the capacitor voltage on the dc voltage harmonics, the dc current which charges the capacitors is varied over a range of operation. Fig.2.5 shows the dc voltage harmonics for the six-pulse operation of the inverter. Dc side harmonics are higher than that of normal bridge operation.

The current harmonics for both natural and forced commutated inverters are mainly dependent upon the overlap angle. The ac current waveform is approximately a square wave which

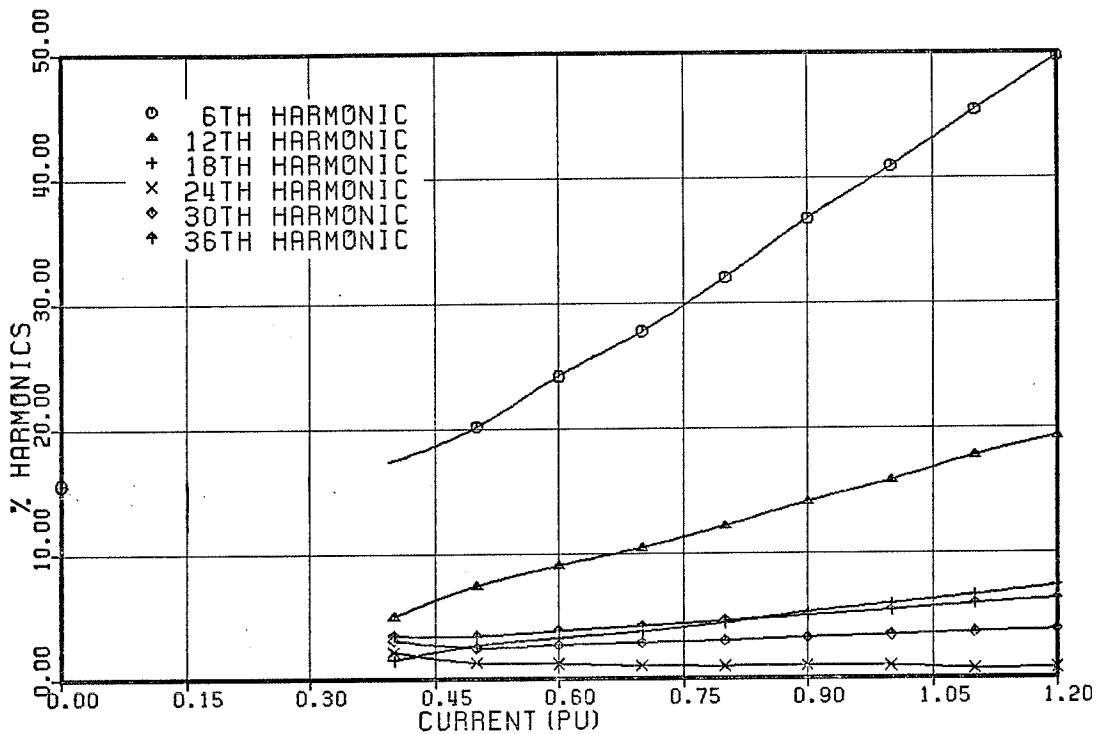


Figure 2.5: Dc voltage harmonics

has a fixed harmonic content not dependent on the dc current. It is the overlap angle which introduces the deviation from the fixed percentage harmonic content of the square waveform. It is shown that for the inverter operation with delay angle around  $180^\circ$ , the overlap angle is almost independent of the dc current [11]. Therefore ac current harmonics are calculated for such a delay angle at unity power operation (Fig.2.6). Ac current harmonics are almost at the same level with the naturally commutated inverter.

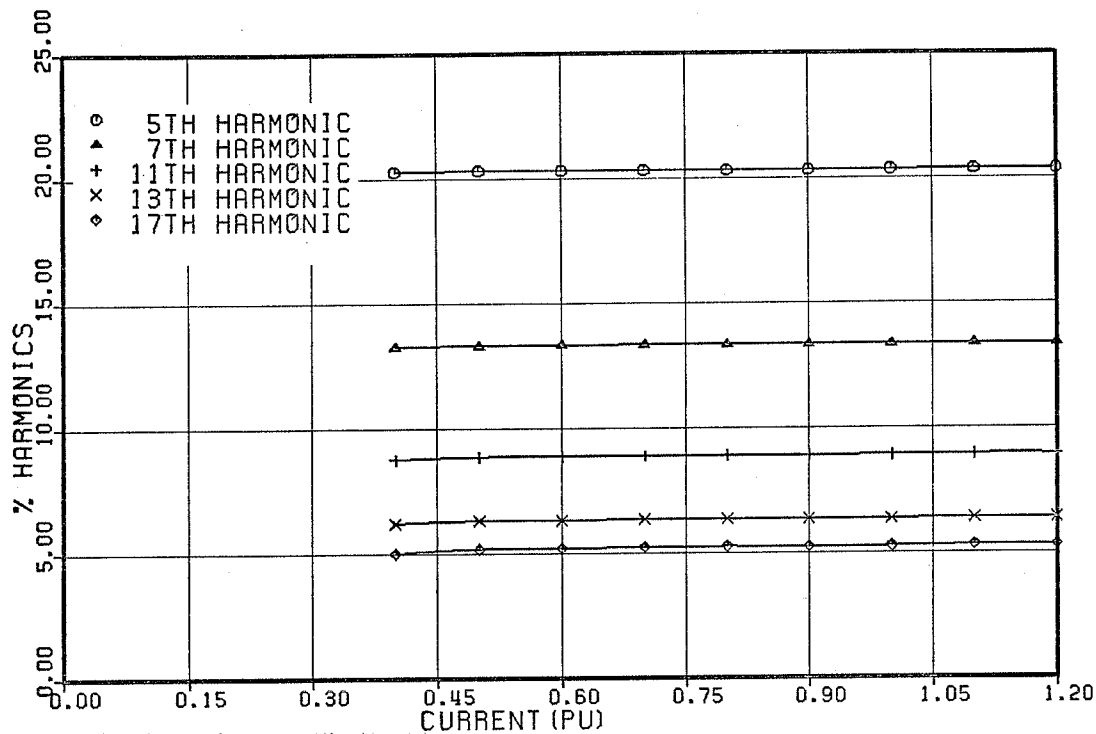


Figure 2.6: Ac current harmonics

## 2.4 TWO-STEP FORCED COMMUTATION SCHEME

### 2.4.1 The Circuit Diagram and Operation of the Circuit

The circuit diagram of the scheme is given in Fig.2.7. Main valves have exactly the same firing sequence as in normal bridge (Fig.2.8). Assume valves 1 and 2 are conducting and 3 is going to take over from valve 1, then instead of firing valve 3 directly, valve 7 is pulsed first. The capacitor is charged in the direction shown during the transfer of current from valve 6 to valve 2. The capacitor voltage applied across valve 1 and the transformer winding turns valve 1 off assuming the charge is sufficiently large. Hence, the current in the positive group is transferred from valve 1 to valve 7. Then the load current  $I_D$  coming from

the negative group valve flows only through one of the transformer windings, the capacitor and valve 7, therefore charging the capacitor in the opposite direction. When the capacitor C is sufficiently charged, main valve 3 starts to take over current from valve 7. Since the capacitor is charged in the opposite direction, it reverse biases valve 7, and therefore the transfer of current from valve 7 to valve 3 is accomplished. Until valve 8 is fired, the capacitor voltage remains unchanged. Then again the current passes through only one of the transformer windings, the capacitor and the auxiliary valve 8 until the current is transferred from valve 8 to next main valve 4. The other transfers between the other main valves in positive and negative groups occur in a similar manner. The capacitor current waveform consists predominantly of the third harmonic.

#### 2.4.2 Program Results and Discussion

A program is developed to observe the transient as well as the steady state performance of the two-step forced commutated inverter. Analysis performed by Busemann {2} is based on a number of assumptions and is only valid for the steady state operation of the circuit while the program developed here can handle transient analysis, as well as ac faults and harmonic analysis. The modelling and solution algorithms are similar to that of the series capacitor commutated inverter. The steady state results obtained by the

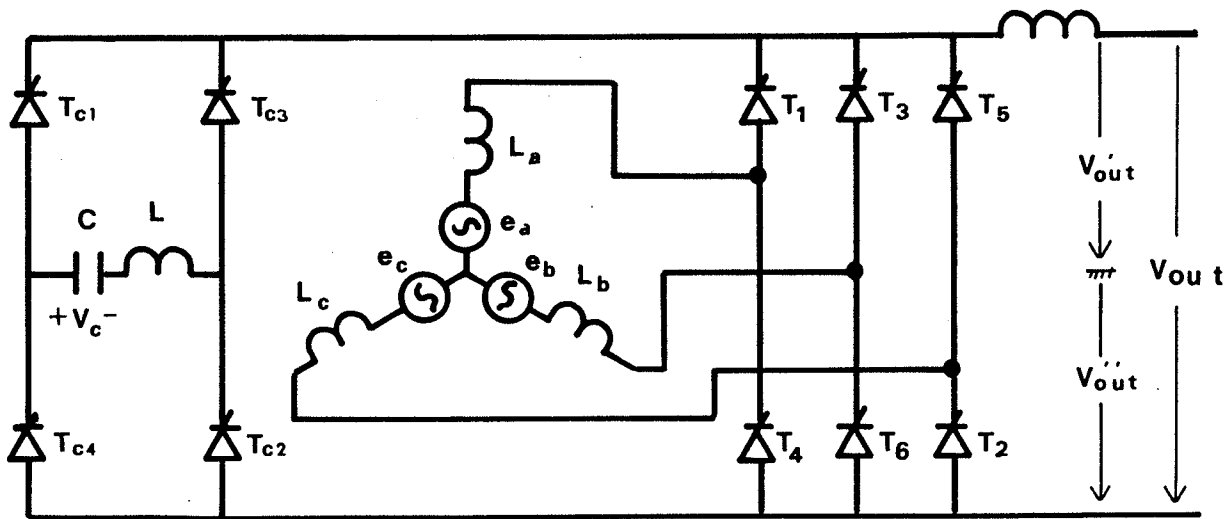


Figure 2.7: Circuit diagram of the two-step forced commutation circuit

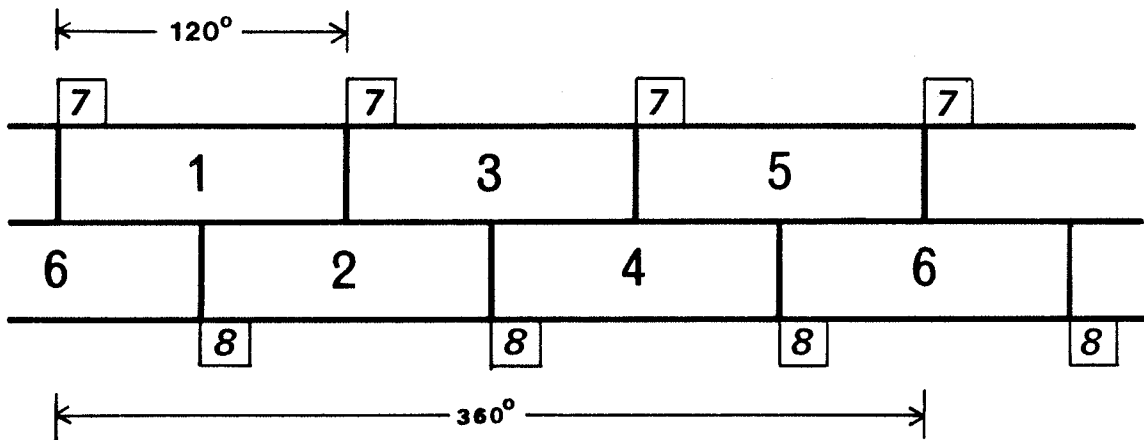


Figure 2.8: Firing sequence of main and auxiliary valves for two-step forced commutated scheme

program are in agreement with those obtained by Busemann. In order to start-up the inverter, the capacitor connected between the neutral of the converter transformer and the auxiliary valves should have appropriate voltage with the

correct polarity as it was described in the previous section to handle the first commutation.

Figure 2.9 shows some typical waveforms for the two-step forced commutated inverter working at a delay angle of  $180^\circ$  after reaching the steady-state. The first overlap angle is about 4-5 electrical degrees for the parameters given in the figure. The capacitor charges up to 1.5 pu in both directions. As seen in Figure 2.9, the maximum forward and reverse voltages across the valve which extinguishes at  $t = 0.0$  s of the waveforms are about 2.0 pu. The output voltage has some ripples. This is due to the fact that output dc voltage is measured at the converter side of the smoothing reactor. Since the delay angle is about  $180^\circ$ , the average value of the output has a negative value.

Fig.2.10 shows peak forward and reverse voltages across the main valve over the range of operation along with that for natural commutation. As seen from the figure, peak voltages in forced commutation are almost equal to those of natural commutation for delay angles less than  $110^\circ$ . As the delay angle increases, the stresses across the main valves in the forced commutated scheme increase. The maximum valve stress occurs at a delay angle of about  $220^\circ$  at which natural commutation is not possible. It is obvious that as the dc current increases the valve stresses will be further increased as in the series capacitor commutated scheme. In order to reduce the valve stresses when controlled power re-

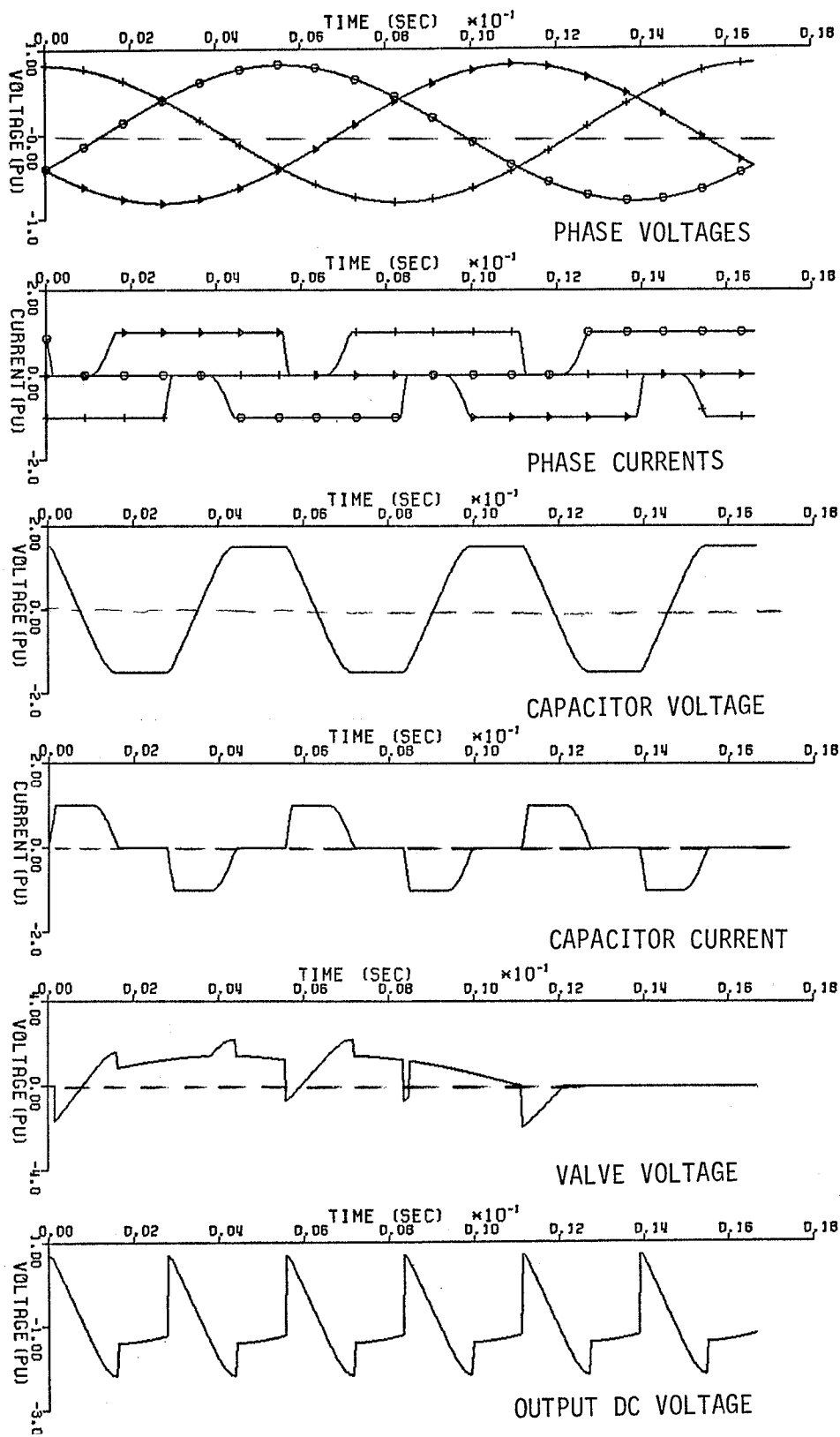


Figure 2.9: Various waveforms of two-step forced commutation circuit  $e_p=0.8165$  pu ( $V_{LL}=1.0$  pu),  $X_L=0.111$  pu,  $I_d=1.0$  pu,  $X_C=6.0$  pu,  $\alpha = 180^\circ$

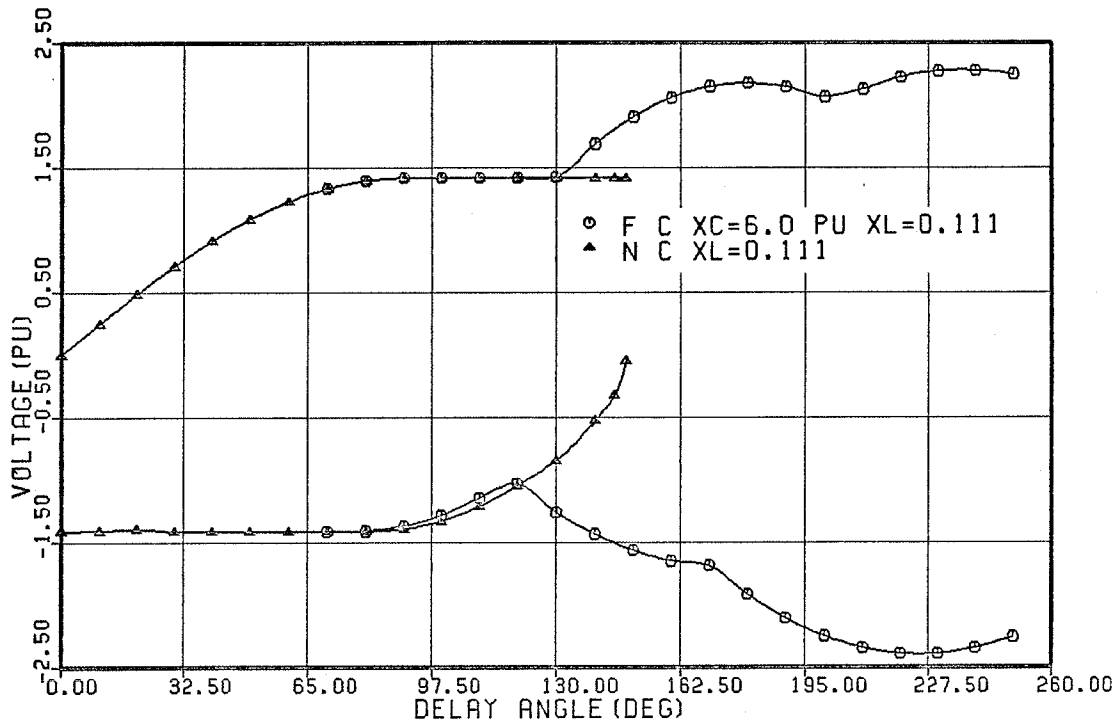


Figure 2.10: Peak valve voltages

versal is desired, the same precautions that were stated for the series capacitor scheme can be applied. Again it is the capacitor voltage which contributes to the valve stresses. Comparison of this scheme with the series capacitor scheme indicates that although the main valve stresses are less, two additional valves of full voltage rating and reduced current rating and associated controls are required. Complete four-quadrant operation is not possible with this scheme.

Using the harmonics program, ac side current and dc side voltage harmonics are studied for the steady state operation. The dc output voltage is affected by the voltage across the capacitor. Therefore to observe the effect of

the capacitor voltage on the dc voltage harmonics, dc current which charges the capacitor is varied. Fig.2.11 shows the dc voltage harmonics as a percentage of the average voltage for the range of current at which forced commutation is possible. Dc side harmonics are much higher than in the normal three phase bridge operation, and are comparatively larger than those of series capacitor commutated scheme.

Fig.2.12 shows the ac current harmonics as a percentage of the fundamental current versus the dc current. The delay angle is assumed to be  $180^\circ$ . Since the capacitor is connected through the neutral of the inverter, triplen harmonics are introduced unlike normal six-pulse operation and series capacitor scheme. But with a  $\Delta$  connected primary winding or with a  $\Delta$  connected tertiary winding, the triplen harmonics will be prevented from entering the ac system and they will just circulate within the  $\Delta$  windings. The other harmonics are equivalent to those of a normal six-pulse bridge.

## 2.5 ONE-STEP FORCED COMMUTATION

### 2.5.1 The Circuit Diagram and Operation of the Circuit

The circuit diagram of the scheme is given in Fig.2.13. The operation of this circuit is different than the normal six-pulse bridge operation. The converter consists of two bridges which are connected by the capacitor C between the converter transformer neutrals. Two commutations take place

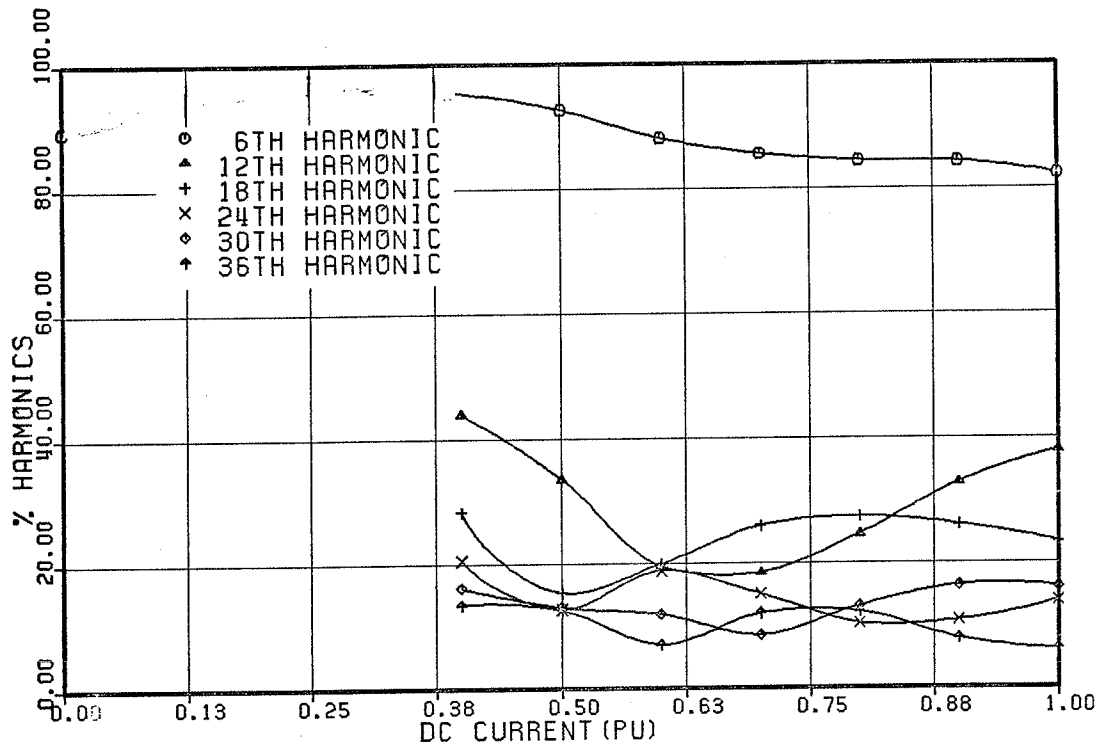


Figure 2.11: Dc voltage harmonics

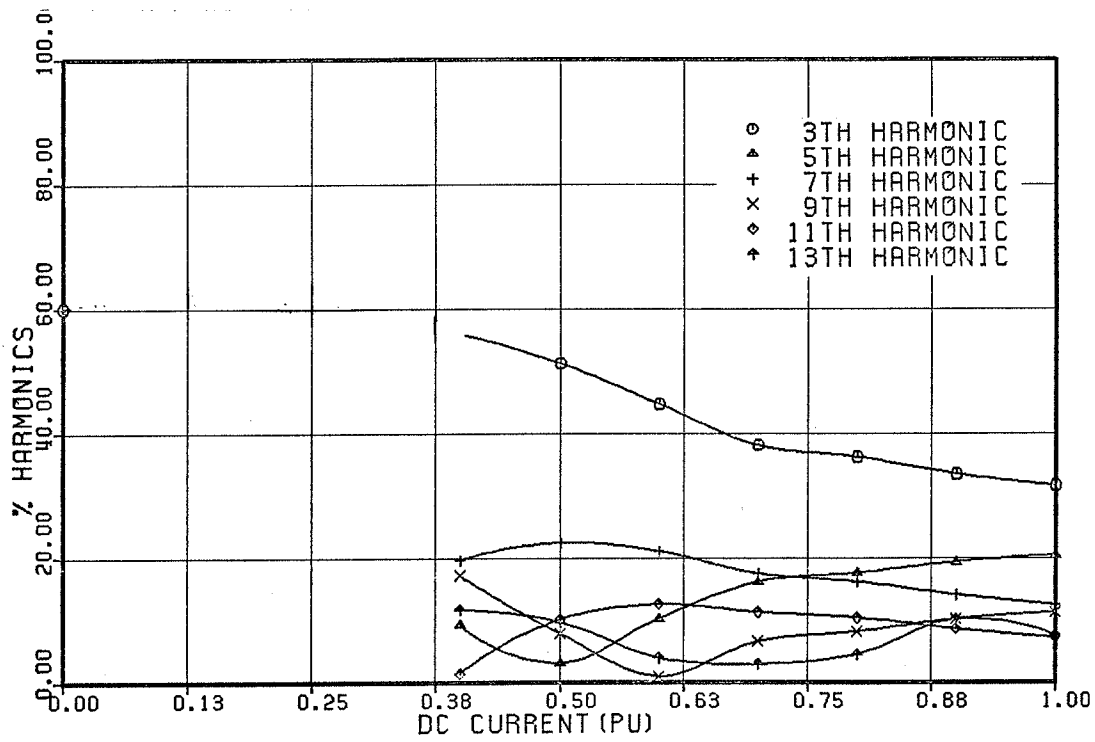


Figure 2.12: Ac current harmonics

simultaneously in the positive and negative groups unlike the six-pulse operation (Fig.2.14). Therefore the direction of the current through the capacitor changes once every one-sixth of a cycle. During the commutation, the current in the commutating loops, hence the voltage of the capacitor connected in between the two bridges is changing nonlinearly. Therefore the state equation solution should be performed. However after the completion of the commutation, the constant dc current will be flowing through the capacitor. Since the state equation solution is quite time consuming, a direct solution method is preferred to solve the circuit for the rest of the one sixth of a cycle.

#### 2.5.2 Program Results and Discussion

A program has been developed to study the transient and steady state behaviour of the one-step forced commutation circuit. Modelling and solution algorithms were already outlined for the previous schemes and hence will not be repeated here.

Fig.2.15 shows some typical waveforms for the one-step circuit working at a delay angle of  $180^\circ$  in steady state. Capacitor charges to peak voltages of about 1.5 pu during the linear charging period which follows a short overlap period (about 7-8 degrees). The maximum forward and reverse voltages across the valve which extinguishes at  $t = 0$  s are about 3.0 and 1.3 pu, respectively. The output voltage is

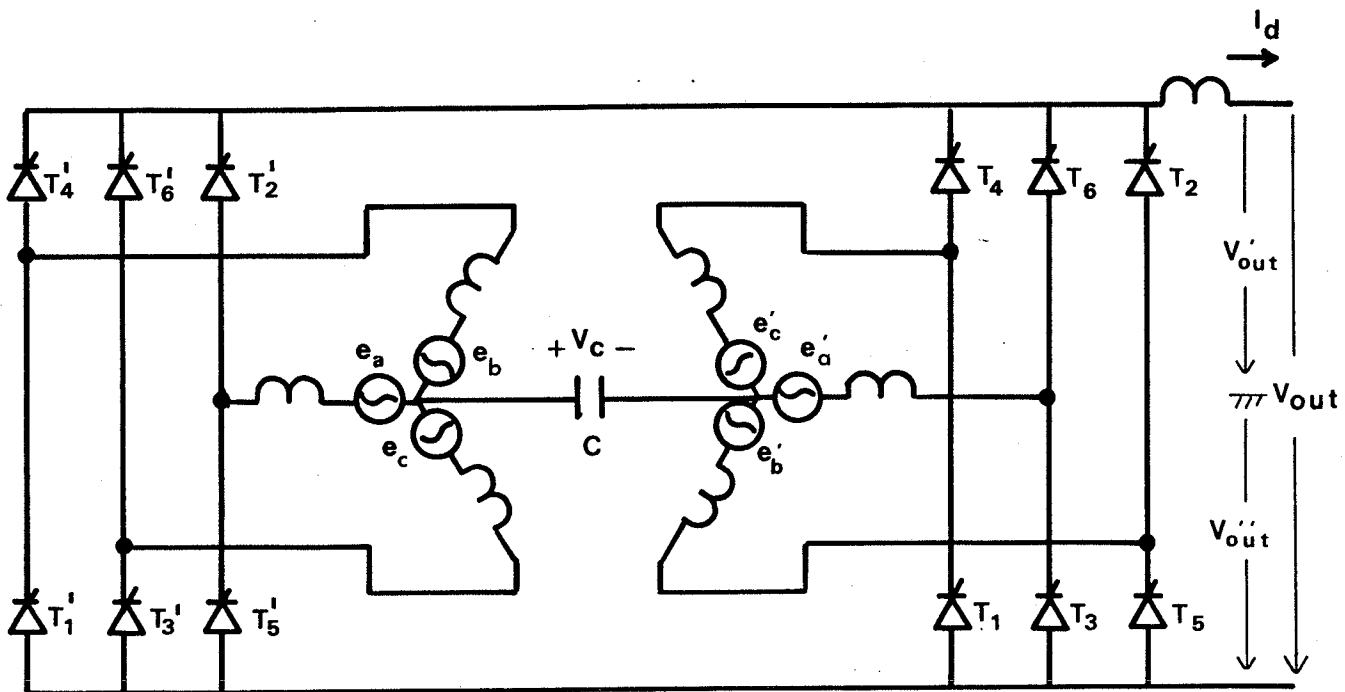


Figure 2.13: Circuit diagram of one-step forced commutation circuit

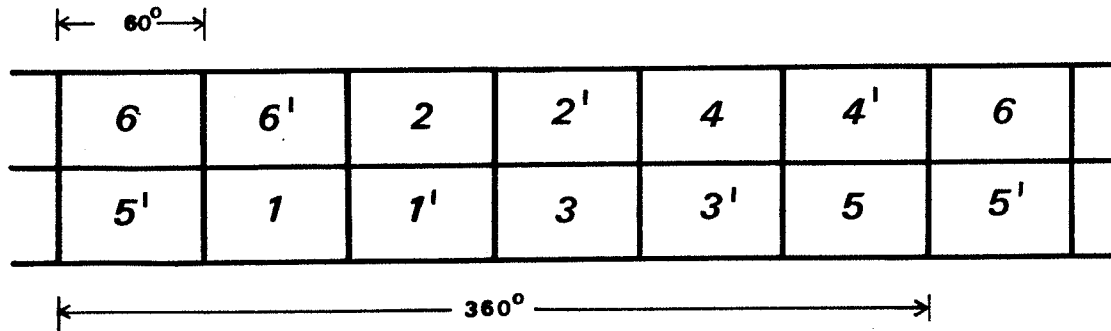


Figure 2.14: Firing sequence of valves in one-step forced commutation scheme

periodic with a period of  $60^\circ$  and its average value is negative since the inverter is working at  $\alpha = 180^\circ$ .

Fig.2.16 shows peak forward and reverse voltages across the valves. Peak voltages are much higher than those of

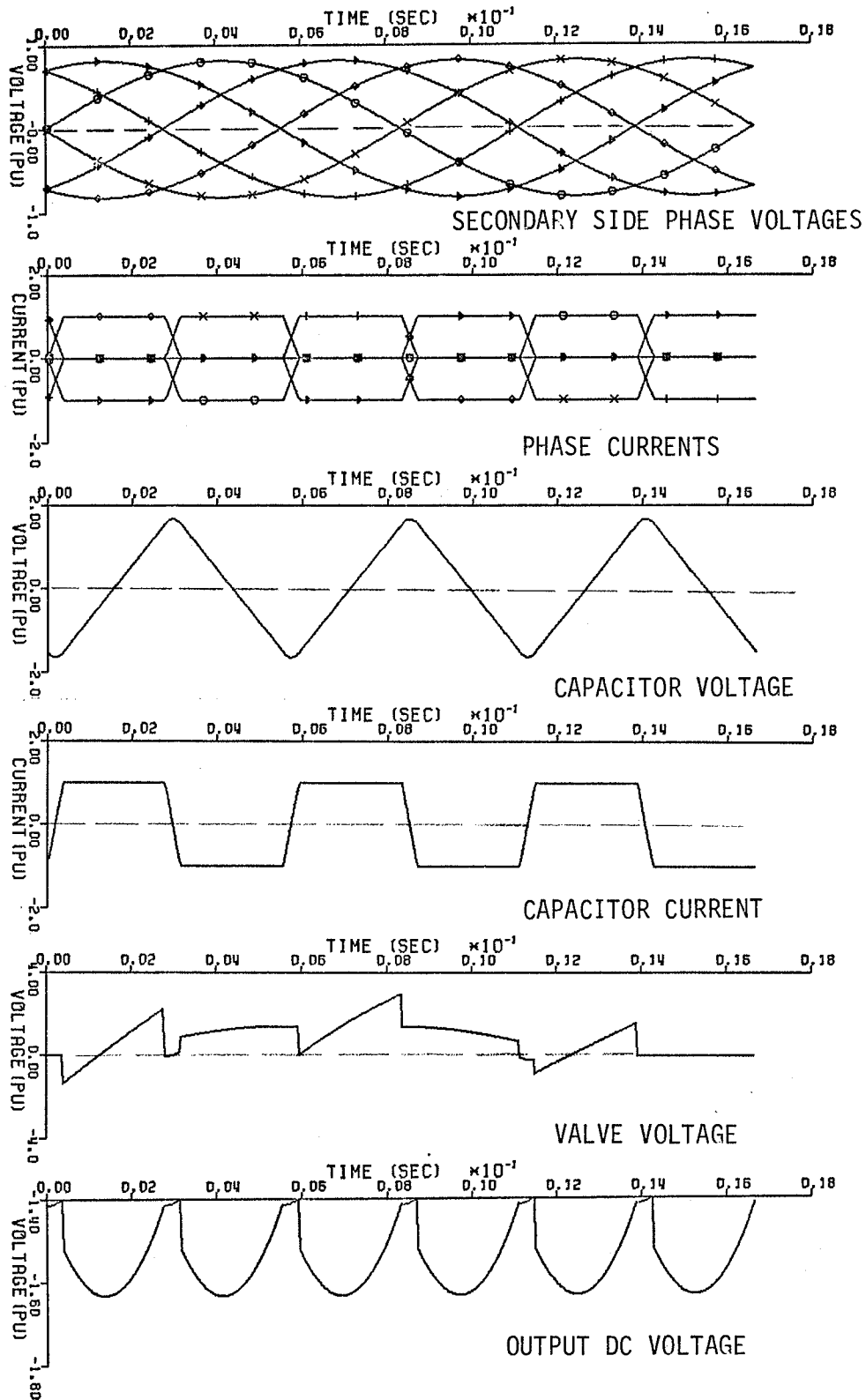


Figure 2.15: Various waveforms of one-step forced commutation circuit  $e_p = 0.8165$  pu ( $V_{LL} = 1.0$  pu),  $X_L = 0.111$  pu,  $I_d = 1.0$  pu,  $X_C = 3.4$  pu,  $\alpha = 180^\circ$

natural commutated inverters for delay angles less than  $145^\circ$ . As the delay angle increases, peak voltages decrease to some extent.

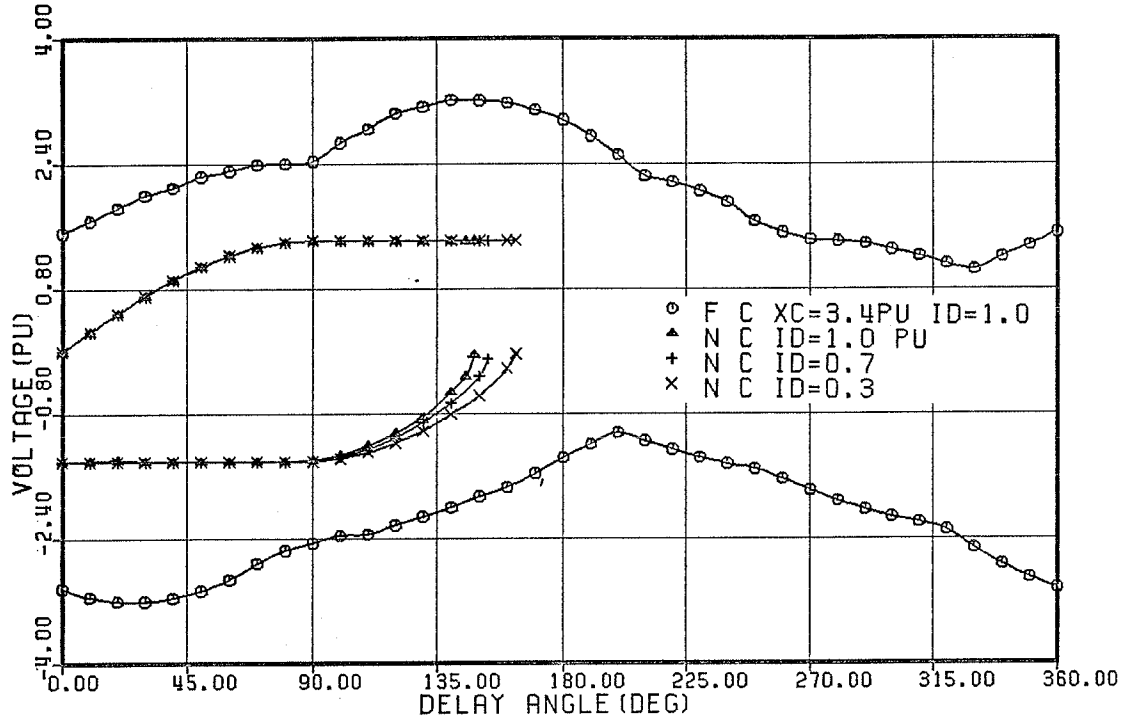


Figure 2.16: Peak valve voltages

Figures 2.17 and 2.18 show dc voltage and ac current harmonics, respectively as a percentage of the fundamental versus the dc current assuming the inverter is working with a delay angle of  $180^\circ$  in steady state. Dc side harmonics are at the same level as with natural commutation. As expected triplen harmonics existed on the ac side unlike the normal bridge operation due to connection between the transformer neutrals. Other than that, harmonic distortions are at reasonable levels compared with the normal bridge operation.

To eliminate the triplen harmonics, either a delta connected primary or a delta tertiary winding is needed in the converter transformer. Although the voltage stresses and current rating of the valves in this scheme are reduced when compared to the series capacitor scheme, two complete bridges with associated converter transformers and controls are required.

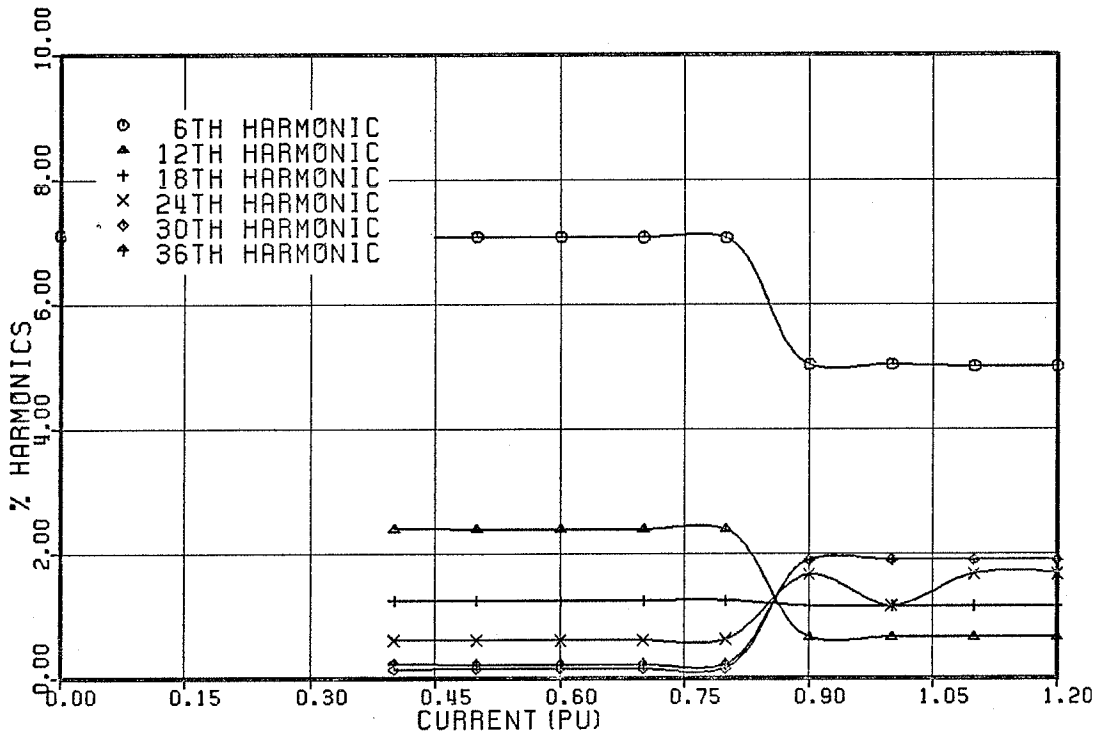


Figure 2.17: Voltage harmonics

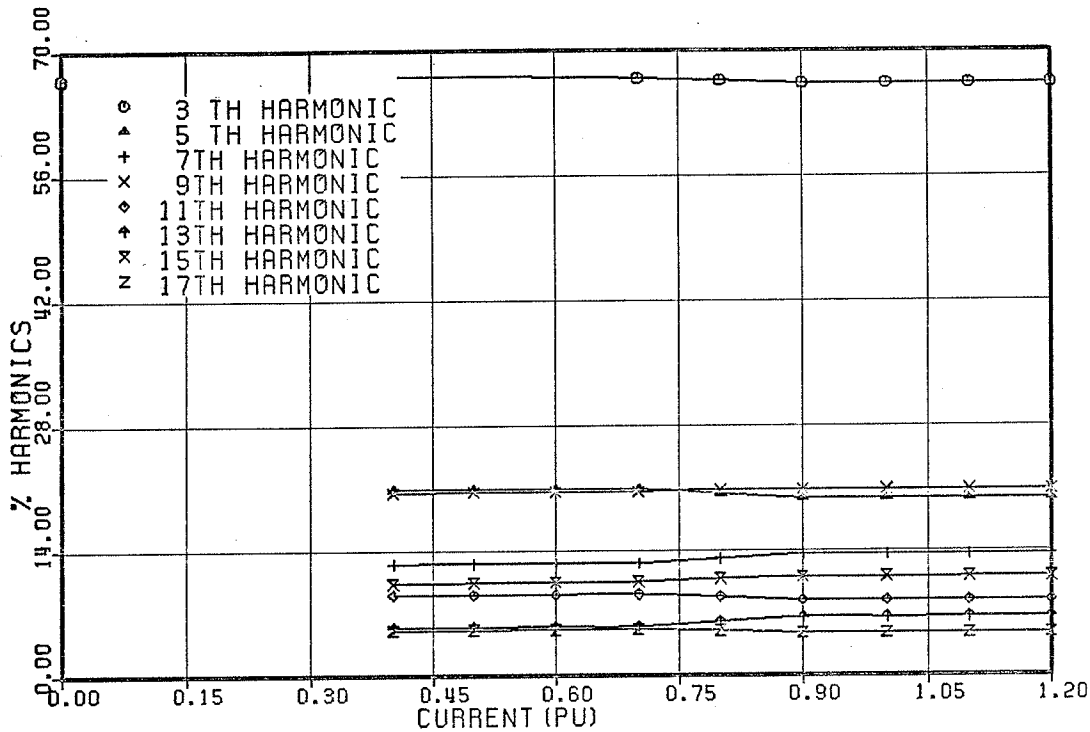


Figure 2.18: Current harmonics

2.6 A FORCED COMMUTATED SERIES TAP (DC CHOPPER SCHEME)

Most of the HVDC installations are point to point systems having a long transmission distance. Although in most cases, the dc line travels in rural areas and small towns, it might be difficult to tap the line using a naturally commutated inverter for those small communities because of the lack of a strong ac system to supply the commutating voltage. It might be possible to use the dc line itself as the source to develop the commutating voltage. A dc-ac machine set can be used for such a purpose although it will certainly have a low efficiency and high maintenance and operating costs {16}. A forced commutated tap might overcome all those difficulties since it does not need any commutating

voltage and reactive power compensation from the ac system. For a small tap power rating, a series tap might be more economical than a parallel tap because of the cost of dc circuit breakers.

### 2.6.1 The Circuit Diagram and Operation of the Circuit

The circuit diagram of the forced commutated series tap is shown in Fig.2.19 . Assume valves 1 and 2 are already conducting and valve 3, is going to take over from valve 1. But before 3 takes over, a short circuit across the tap should be applied. For this purpose, at a certain delay angle with reference to the point at which the phase voltage  $e_b$  becomes greater than phase voltage  $e_a$ , i.e. when incoming valve 3 is forward biased, valve 4 is fired. To turn-on valve 4, it should be already forward biased. This condition is satisfied in the range of delay angle from  $60^\circ$  to  $240^\circ$  theoretically (i.e. neglecting the effect of the overlap due to transformer reactance). The firing sequence of the main and auxiliary valves are given in Fig.2.20 . The transfer of current from valve 2 to valve 4 cannot take place instantaneously because of the transformer impedances  $L_a$  and  $L_c$  on phases a and c. The duration of the overlap will be dependent upon the dc current and the commutating impedance. When the overlap period is completed, valves 1 and 4 will be short circuiting the bridge for a certain period of time depending upon the real power required by the ac

system. In order to complete the by-pass period, the auxiliary valves  $T_{C1}$  and  $T_{C2}$  are pulsed at the same time. Assuming that the capacitor is charged with the polarity shown in the figure during the operation of  $T_{C3}$  and  $T_{C4}$  in the previous one sixth of a cycle,  $T_{C1}$  and  $T_{C2}$  turn-on. The transfer of current from the by-passing bridge arm to auxiliary valves takes place almost instantaneously since the inductive impedance in the commutation loop is very small. (No transformer impedance is involved in the commutation. The only inductance in the commutating loop is the small  $di/dt$  protection inductance.) At the same time, firing pulses are also applied to incoming main valves 2 and 3. The dc current flowing through the auxiliary valves charges the capacitor C. Hence the capacitor voltage reverses its polarity. When the capacitor voltage reaches a certain level, the incoming valves will be forward biased, and will turn-on since they were already pulsed. Because of the inductive impedances in phases b and c, the transfer of current from the auxiliary branch to main valves will also introduce an overlap period. After the completion of the commutation there will be no current flowing through the capacitor and the main valves will be conducting constant dc current  $I_d$ . The similar operation will take place for a commutation in the negative group. But this time, capacitor is charged in the opposite direction. Therefore auxiliary valves  $T_{C3}$  and  $T_{C4}$  will be turning on when they are pulsed simultaneously.

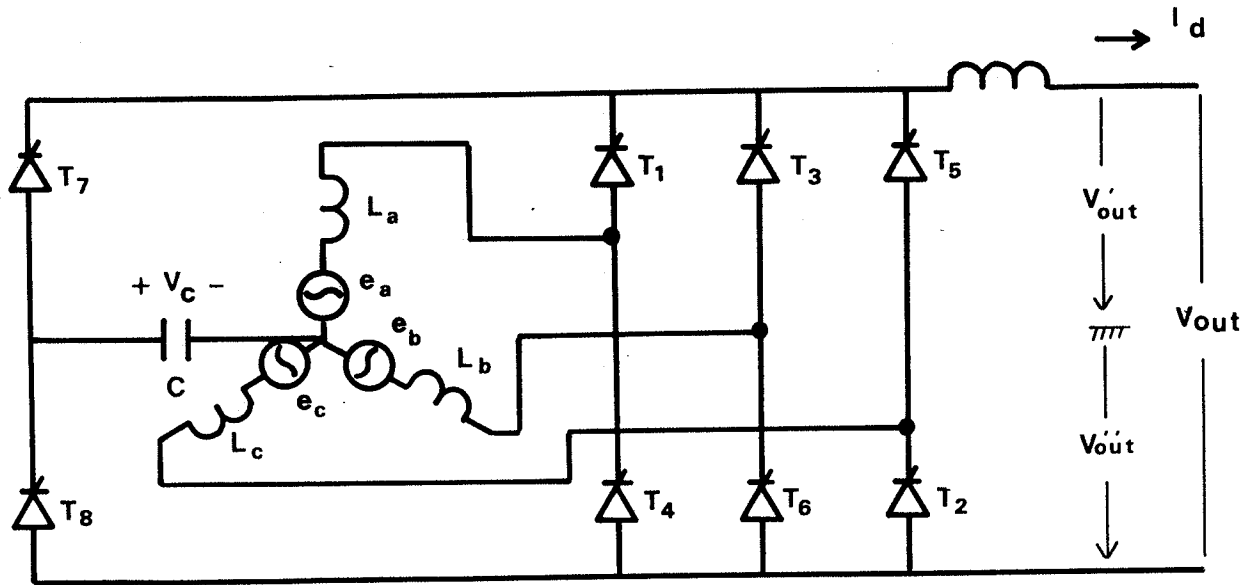


Figure 2.19: Circuit diagram of the dc chopper scheme

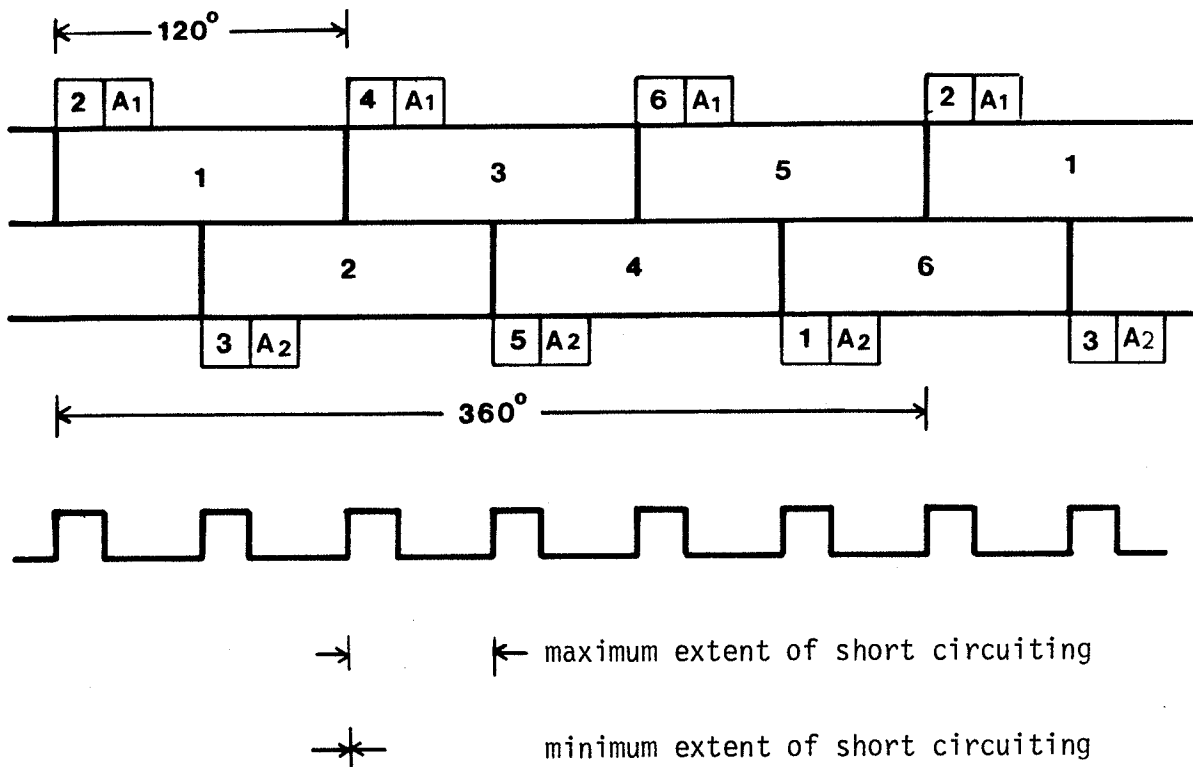


Figure 2.20: Firing sequence of main and auxiliary valves for dc chopper scheme

### 2.6.2 Program Results and Discussion

A program is developed to study the transient as well as steady state performance of the dc chopper scheme. For starting the system up, the commutation capacitor should be charged to appropriate voltage by some auxiliary supply. A possible circuit configuration was proposed by Sood and Bowles {5,6}.

Fig.2.21 shows some typical waveforms for the dc chopper scheme working with a delay angle of  $180^\circ$ . With the given parameters the commutation capacitor charges up to 3.5 pu in both directions. It is assumed that the by-pass period lasts for about  $10^\circ$ . (This duration will be defined depending upon the power requirement of the ac system.) As seen from the figure the output voltage is zero during the by-passing periods. The peak forward voltage across the valves is about 4.0 pu.

Fig.2.22 shows the peak forward and reverse voltages across the main valve over the range of operation. As seen from the figure, peak voltages for forced commutation are almost equal to those of natural commutation for delay angles less than  $110^\circ$ . As the delay angle increases, peak valve stresses increase.

Using the harmonics program, ac side current and dc side voltage harmonics are studied assuming the inverter is working in steady state. Figs.2.23 and 2.24 show dc voltage and ac current harmonics, respectively over the range of opera-

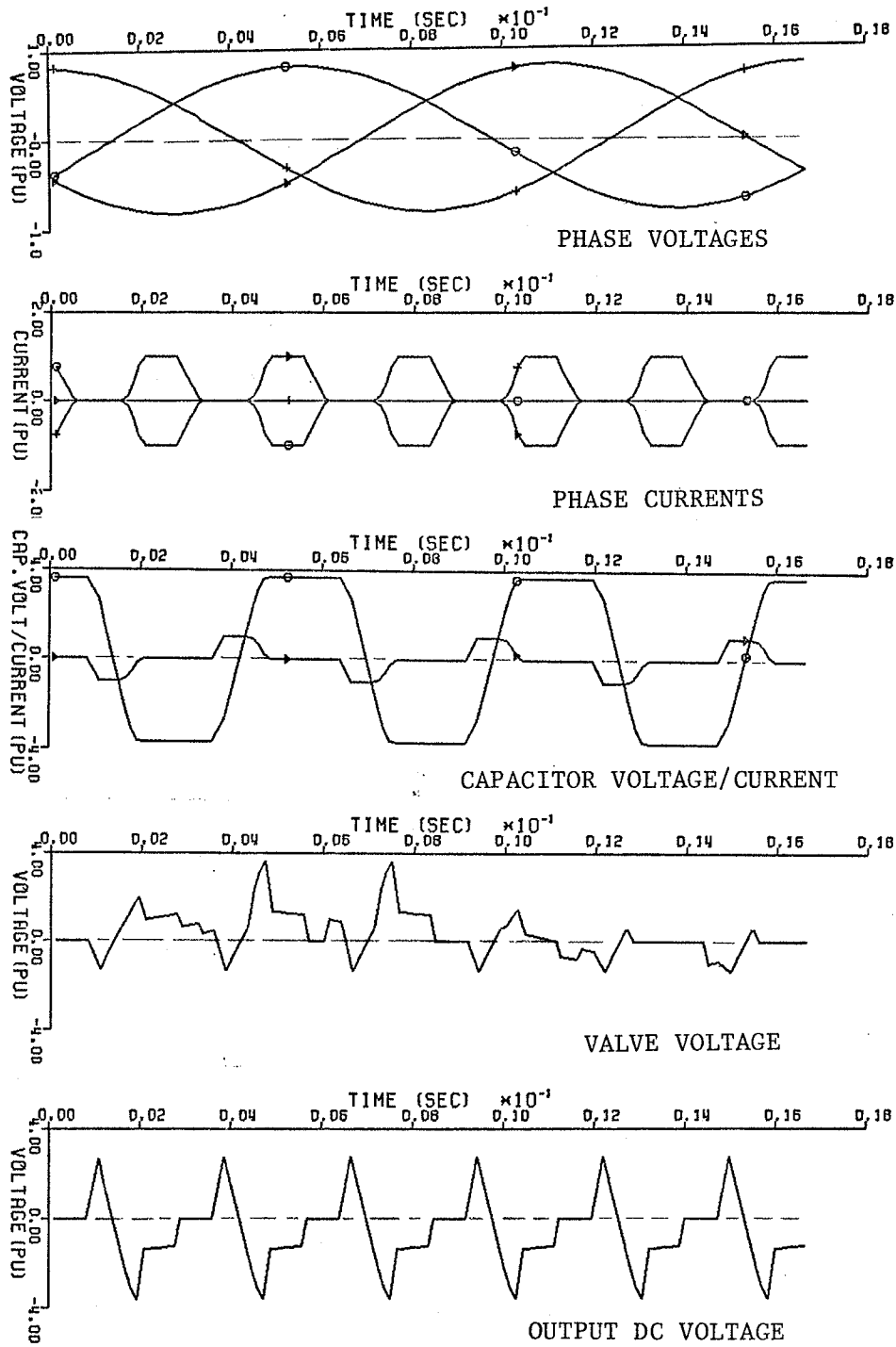


Figure 2.21: Various waveforms for the dc chopper circuit  
 $e_p = 0.8165$  pu ( $V_{LL} = 1.0$  pu),  $X_L = 0.111$  pu,  
 $I_d = 1.0$  pu,  $X_C = 22.0$  pu,  $\alpha = 180^\circ$ ,  
 by-pass period =  $10^\circ$

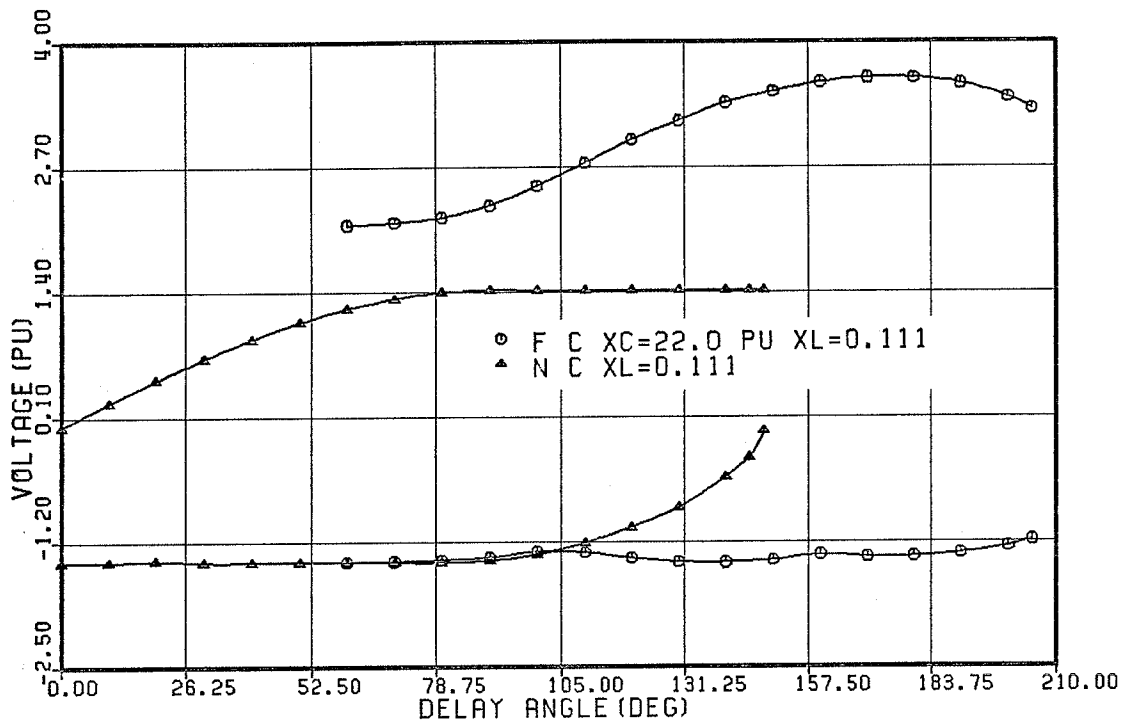


Figure 2.22: Peak valve voltages

tion. As seen from the figure, dc voltage harmonics are very high since the voltage is chopped several times during the cycle. Ac side current harmonics are higher than those of a normal bridge and are almost independent of delay angle but vary considerably with the short circuit period. Since the output voltage is zero during the by-pass periods, dc voltage harmonics are also dependent on the by-pass period. As the by-pass period becomes larger, all dc side voltage and the predominant ac side current harmonics increase [12].

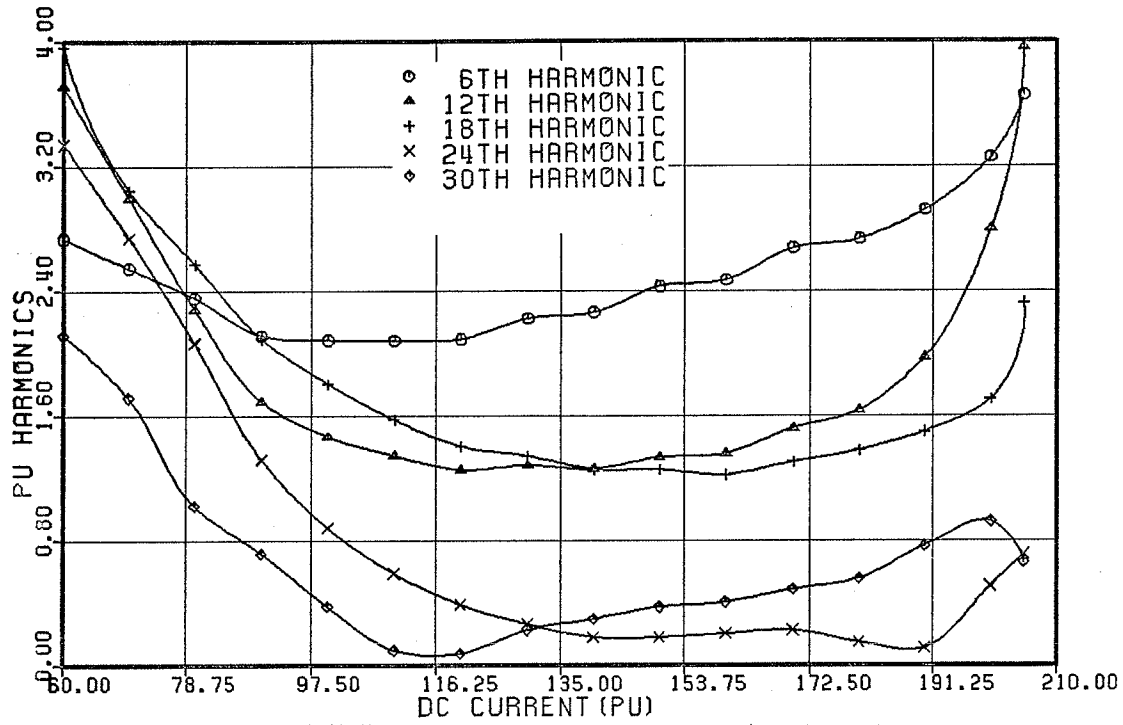


Figure 2.23: Dc voltage harmonics

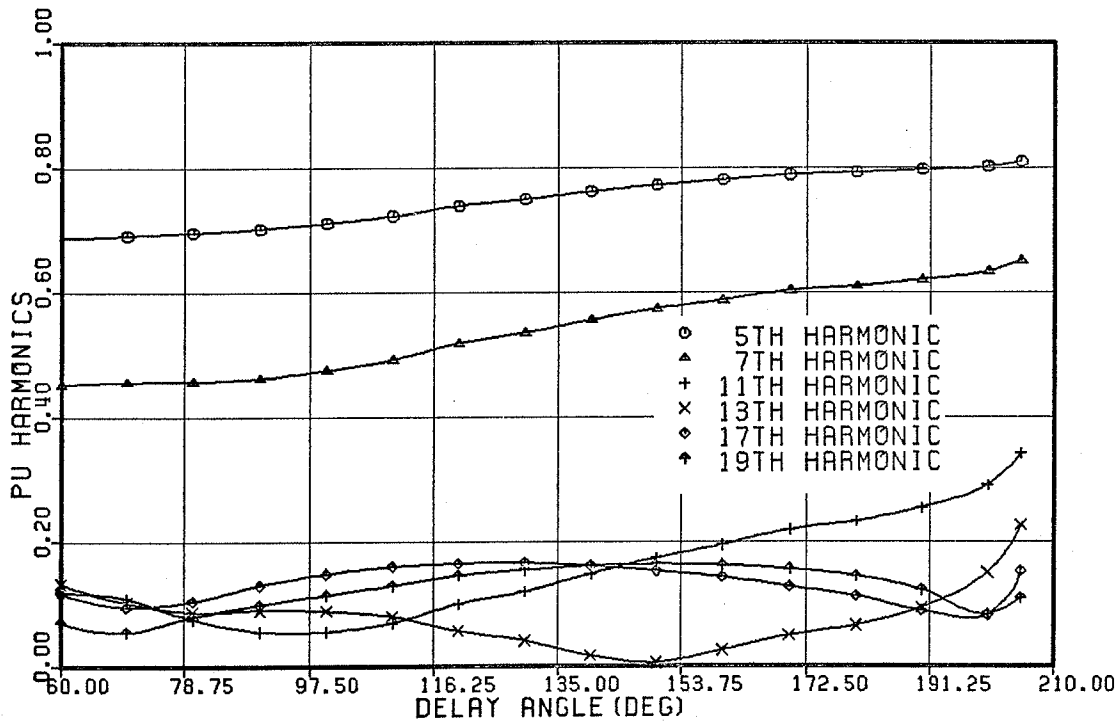


Figure 2.24: Ac current harmonics

## 2.7 CONCLUSIONS

Most of the forced commutation schemes require additional auxiliary valves, of full voltage rating, to connect the capacitor across the out-going valves to provide the commutation voltage. The two-step forced commutation circuit uses two additional valves; the one-step circuit uses a second bridge of full voltage rating in addition to the normal bridge. The dc chopper scheme uses a minimum of two auxiliary valves. In the series capacitor commutation scheme, the number of valves is exactly the same as in the normal three phase bridge. Around unity power factor operation, all schemes introduce higher voltage stresses across the valve in forward and reverse directions.

The capacitor reactive power ratings of two-step and series capacitor commutated circuits for unity power factor operation are around the same order of reactive power as that which is required for reactive power compensation in a naturally commutated inverter. There is a reasonable saving of the capacitor kvar rating with the one-step forced commutation scheme.

With all forced commutation schemes, the utilization of the converter transformer is improved, since the inverter can easily be designed to operate at unity or close to unity power factor in the steady state.

With one-step and two-step forced commutation schemes, the secondary side of the converter transformer must be con-

nected in wye for the commutation capacitor connection. This might result in a restriction for the twelve-pulse operation as it is the practice to connect the primary side of the transformer in wye with a grounded neutral in order to eliminate zero sequence currents and for insulation stresses.

Triplen harmonics arise with one-step and two-step forced commutation schemes because of the arrangement of the commutation capacitor. In order to eliminate the triplen harmonics a delta connected tertiary winding is required. This will increase the transformer costs.

Harmonic distortion on the dc side is lowest with the one-step forced commutation scheme. Ac side harmonics with one-step, two-step and series capacitor schemes are at the same level with those of natural commutation. Both ac side and dc side harmonics are higher with the dc chopper scheme.

Minimum current level is always a restriction with forced commutated schemes since the dc current charges the capacitors. It becomes a more important restriction with the two-step scheme since the capacitor is charged only during a small portion of the one sixth of the cycle.

Based on the above comparative studies the series capacitor commutated inverter was chosen as technically superior to the other forced commutated schemes. The two-step scheme has been chosen by Joetten and Michel [17] and their results and those in Section 2.4 are the same. Both schemes are

technically feasible, the only difference being in the range of operation of the delay angle, the extra number of valves and overall more complexity of the controls in the case of two-step circuit. For the applications discussed in this thesis complete four-quadrant operation was required and therefore the series capacitor scheme was chosen for the following studies.

## Chapter III

### SIMULATION OF A FORCED COMMUTATED INVERTER ON BIPOLE 1 SYSTEM

#### 3.1 INTRODUCTION

In this chapter a large scale point to point HVDC transmission link and terminal ac systems have been simulated using a complete power system model. These original simulation studies were performed to determine the operation of a forced commutated inverter in an actual system. These studies are conducted on Manitoba Hydro's electromagnetic transients program (EMTDC) which includes distributed transmission line models, generalized bridge arrangement with associated damping circuits, electrical machine models, power system components and metering and control devices.

The validity of this simulation program has been confirmed by field and laboratory tests of the various models including all components used in the present studies [18]. As well, the Electric Power Research Institute's multiterminal dc system, has been modelled by others using Bonneville Power Authority's electromagnetic transients program (BPA-EMTP) [19], an industrial standard, and Institut de Recherche d'Hydro Quebec's (IREQ) physical simulator [20]. These studies have been duplicated using EMTDC for the study

of parallel taps discussed in Chapter 5. The results using all three power system simulators were found to be comparable.

This chapter using Manitoba Hydro's Bipole 1 System as a reference, introduces the difficulties of inverting into a weak system from the system point of view and how the difficulties can easily be handled if a forced commutated inverter is used. The chapter includes a brief description of the model of the voltage controller, followed by the results of start-up and various ac and dc side fault studies. The effect of forced commutation on valve stresses and the cost comparison of the terminal is covered at the end of the chapter. The results of all studies completed on this system are included in Reference 21.

### 3.2 INVERSION INTO WEAK AC SYSTEMS

#### 3.2.1 Difficulties with Natural Commutation

The impedance of the ac system observed from the dc side varies with the frequency. But the impedance at fundamental frequency in per unit based on the dc rating, referred to as short circuit ratio (S.C.R.), has an important meaning since it gives the strength and capability of the ac system as far as the reactive power consumption of the converter is concerned. S.C.R. can be written as {22} :

$$\text{S.C.R.} = \frac{V_{LL}^2}{P_d Z}$$

where

$V_{LL}$  = line to line ac voltage (kV),

$P_d$  = dc power transmitted (MW),

$Z$  = ac system impedance at fundamental frequency at the commutating bus-bar (ohms).

An S.C.R. greater than 4.0 pu represents a strong ac system while an S.C.R. less than 2.5 pu represents a weak system. The problems which might arise with such a weak system when supplied by dc power can be outlined as :

- i) Continuous instability problems at middle or low frequencies,
- ii) Ac voltage might fluctuate greatly during ac or dc faults,
- iii) Peak transient overvoltages might arise following any disturbance such as start-up or a fault,
- iv) Recovery time after any disturbance might be longer than that of a strong system.

Even a strong system cannot solve all these problems. Voltage changes, and low frequency stability problems are independent of control type. It is the ac system impedance (magnitude and phase angle) at fundamental frequency which has a major effect on the operation of the converter.

In weak systems large voltage changes on the ac bus-bar are experienced and low voltage stability is not possible. In order to compensate the effects which originate from the size of the ac system, reactive power can be supplied by means of ac shunt capacitors, synchronous condensers or

static compensators. A synchronous condenser having its transient reactance in parallel with the ac system decreases the system impedance resulting in a higher S.C.R. Although static condensers, i.e. switched capacitor banks, are quite cheap and almost maintenance free, they have a slow control response to middle frequency stability and make no contribution to the short circuit level of the system. Static var systems are much faster but again make no contribution to the S.C.C. of the system. For disturbances, a hybrid system of static and synchronous condensers having a large inertia is the best alternative.

### 3.2.2 Solution by Forced Commutation

Forced commutation is quite attractive, especially when inverting into weak systems, because it enables the converter to operate in ranges which are not permitted by means of natural commutation. Thus it is possible for the inverter to rapidly control the amount of real and reactive power supplied to the system to damp out ac system instabilities and limit overvoltages during faults. The requirement for external reactive power compensation is eliminated.

### 3.3 CONTROLS

#### 3.3.1 Current Controller

Since the dynamic load effects will not be considered, a central controller to coordinate the power to be transmitted is not incorporated with the controls. The current order is defined as 1.0 pu.

The current is controlled by the rectifier employing a conventional constant current (C.C.) controller. Measured dc current is fed back and compared with the input current order. The resultant current error is passed through a proportional plus integral controller to produce the desired ignition delay angle or alpha order.

The inverter end is also equipped with a similar current controller having a current margin 10 %. The desired alpha order is passed to the valve group controllers for the pole considered.

#### 3.3.2 Constant Voltage Controller

In natural commutation, in order to keep the power factor of the converter as high as possible, but also to prevent the possibility of commutation failure the "constant extinction angle control" (C.E.A.) also known as "constant gamma control" is employed at the inverter end. However in forced commutation there is no such danger of commutation failure provided that the capacitor voltages which are contributing to the commutation voltage are adequate. Since the inverter

can control VAR flow as well as power flow independently in all four quadrants of operation, the voltage at the commutating bus-bar can be controlled.

To accomplish this control action, a controller is designed and it is observed that it functions successfully. The operation can be outlined as follows :

- i) Measure the rms voltage on the commutating bus-bar,
- ii) Compare the measured voltage with the set value,
- iii) The error signal after being scaled goes into a high gain amplifier. The output of the amplifier defines the alpha order which is fed into the valve group controller.

If the measured voltage is lower than the set value, the delay angle of the valve group is delayed further. This increases the phase displacement between voltage and current phasors, hence consuming less reactive power from the ac system. As it is seen from Fig.3.1, the angle can be increased even beyond  $180^\circ$ , then the current will be more lagging the voltage, it will be leading the voltage phasor. This means converter will be supplying reactive power to the ac system. If the measured voltage is higher than the set value, then reverse action should be taken.

The voltage controller has a select minimum circuit. Hence, the above described constant voltage control action will be effective to define the alpha order only if a sufficient amount of current is flowing through the link.

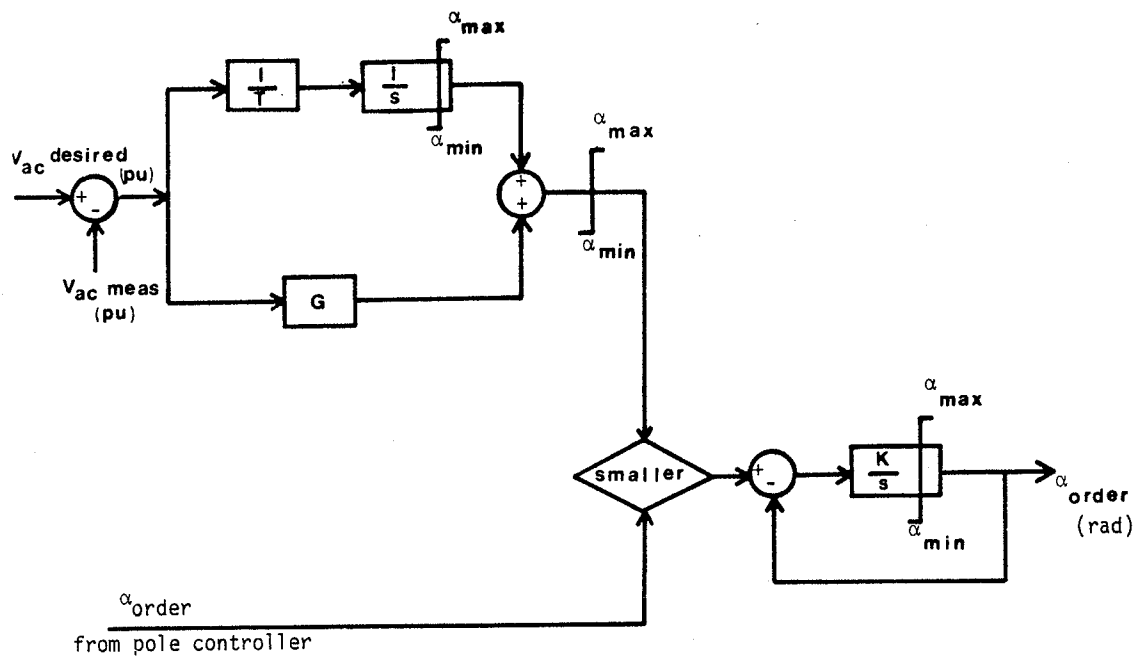


Figure 3.1: Block diagram of constant voltage controller

### 3.4 APPLICATION EXAMPLE

In order to demonstrate that inversion into weak systems is possible without reactive power support by forced commutation, a point to point HVDC system consisting of a forced commutated inverter is studied. The simulation of the system is performed on a digital dc simulator, known as Manitoba Hydro's Electromagnetic Transients Program (MH EMTDC) [18].

A single pole model of Manitoba Hydro's Bipole 1 system is selected as the test system. The single line diagram of the circuit is given in Fig.3.2 with the system data listed in Appendix B. Although, in reality two poles consist of six valve groups in series usually working in twelve-pulse operation, for simplicity and to save computation time, only

one pole with one valve group is modelled. The full ratings of the pole is used by scaling the three valve groups into a single one. Therefore, the operation of the model is studied only in six-pulse operation although these results may be extended to twelve-pulse operation.

To eliminate any control problems which might originate because of the size of the system, the rectifier end ac system is designed as a strong system. The forced commutated inverter is employed at the inverter end of the system. The parameters listed in Appendix B are based on S.C.R. for the receiving end ac system of 1.5 pu at a phase angle of  $70^\circ$ . The value of the commutating capacitor was chosen as 0.9 pu on the hybrid per unit system (Appendix A) which is the minimum value which will give complete four quadrant operation under steady state conditions for rated dc current. As shown in Fig. 2.4, the range of operation of the delay angle becomes limited for lower values of dc current but as the delay angle can still approach  $190^\circ$  for a dc current of 0.3 pu it is not a significant constraint.

### 3.5 RESULTS

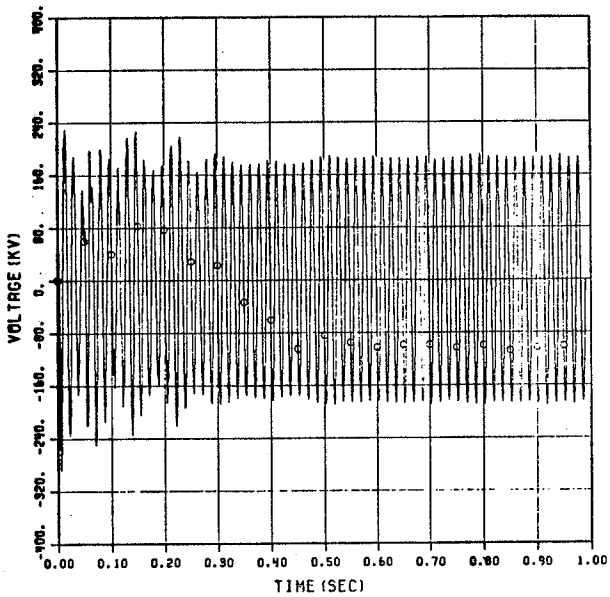
This system is studied for start-up, ac and dc side faults and the valve stresses. Fig.3.3 shows various waveforms during the start-up of the system. As seen in Fig.3.3-a, although there is some distortion on the voltage waveform during starting because of transient disturbances,



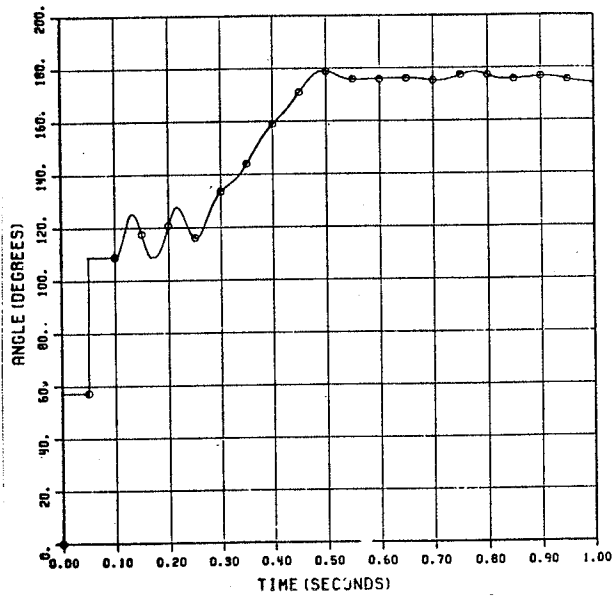
they disappear when the system stabilizes. Fig.3.3-c shows the reactive power supplied into the ac system from the converter. This reactive power is nearly equal to the reactive power generated by the ac shunt filters which indicates the inverter is working near unity power factor. As seen from Fig.3.3-d the ac line to line voltage at the commutating bus-bar is kept at its rated value by means of the constant voltage controller.

Single and three phase ac system and dc line faults are studied on a 1.5 pu S.C.R. ac system at the receiving end. Fig.3.4 shows waveforms of a 3 cycle (50 ms) three phase to ground ac fault at the receiving end system. As shown in Fig.3.4-a, once the fault is sensed the current order is reduced to its fault level, and after clearance is ramped back up at a prescribed rate. The alpha order of the valve group is kept at the fault level during the fault and afterwards the clamp is removed (Fig.3.4-b). As seen in Fig.3.4-c the system settles back to steady state in about 0.5 s.

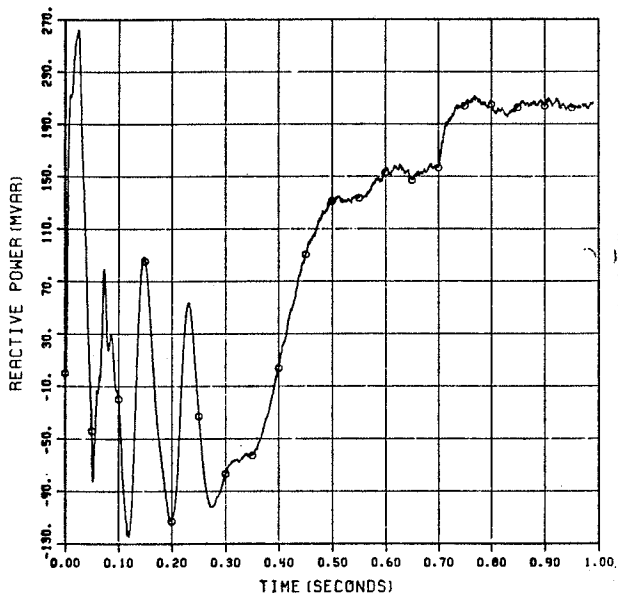
Waveforms for a single phase to ground ac fault at the receiving end system are presented in Fig.3.5. The fault is assumed to be some distance from the inverter, therefore the voltage on the commutating bus-bar does not completely collapse. Fig.3.5-a shows the faulty phase during and after the fault. As is seen from the figures, the system settles in about 0.5 s after the fault occurs. During the fault, the measured rms ac voltage does not collapse, but oscillates and stabilizes after about 0.5 s .



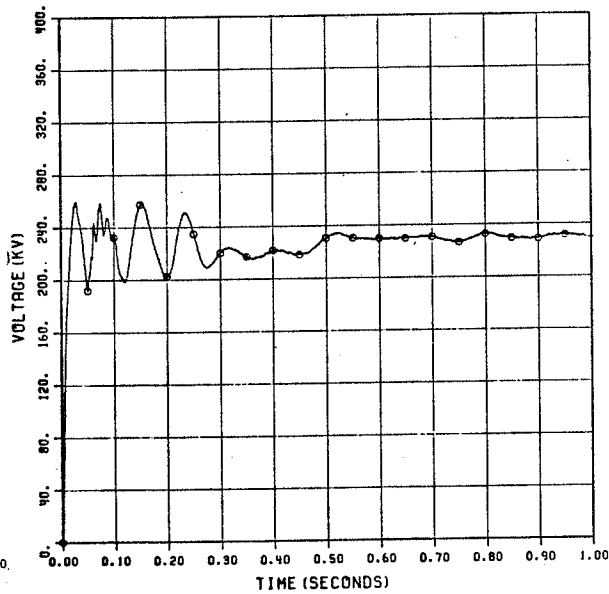
a



b



c



d

Figure 3.3: Various waveforms during the start-up  
 a - Voltage waveform at the commutating busbar,  
 b - Alpha order at the inverter,  
 c - Inverter end reactive power into ac system,  
 d - Measured ac rms voltage (line to line)

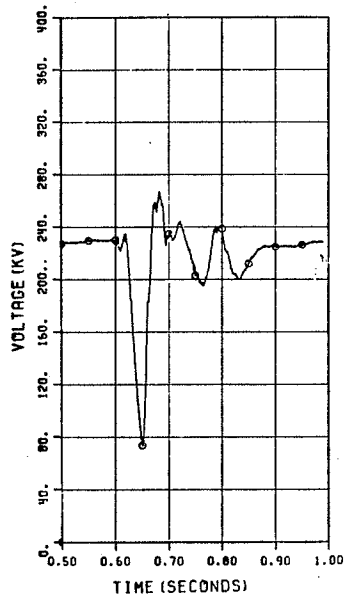
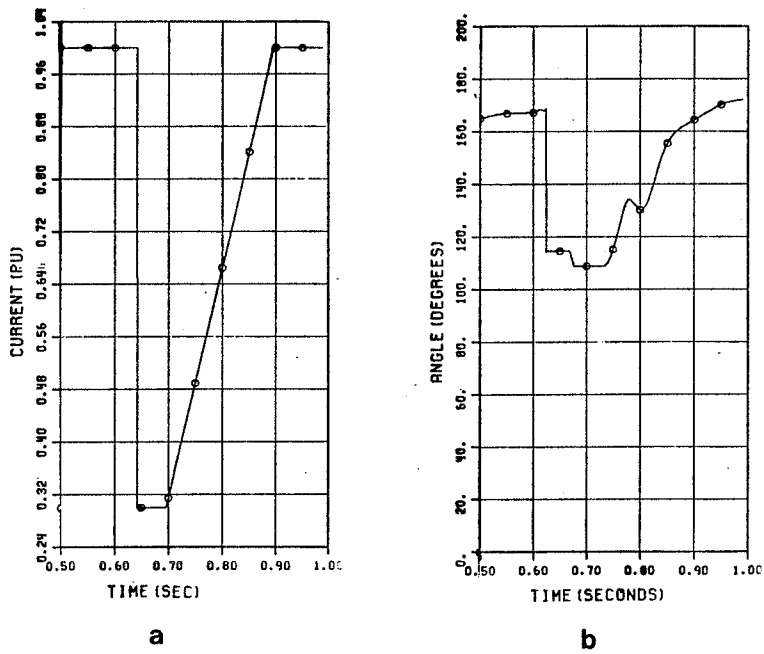
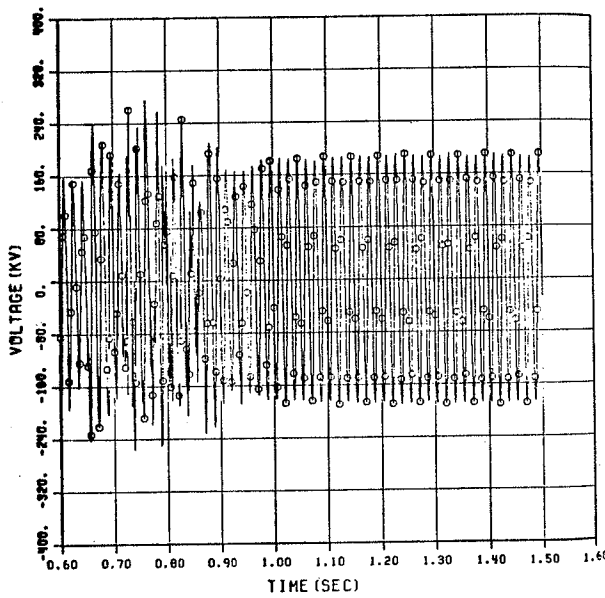
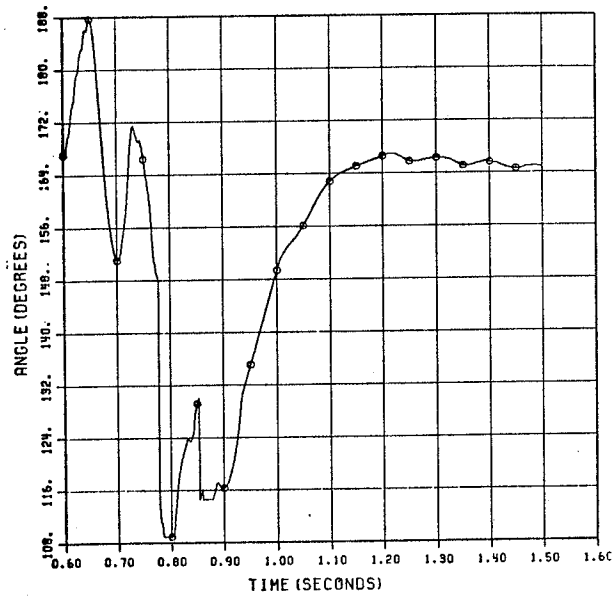


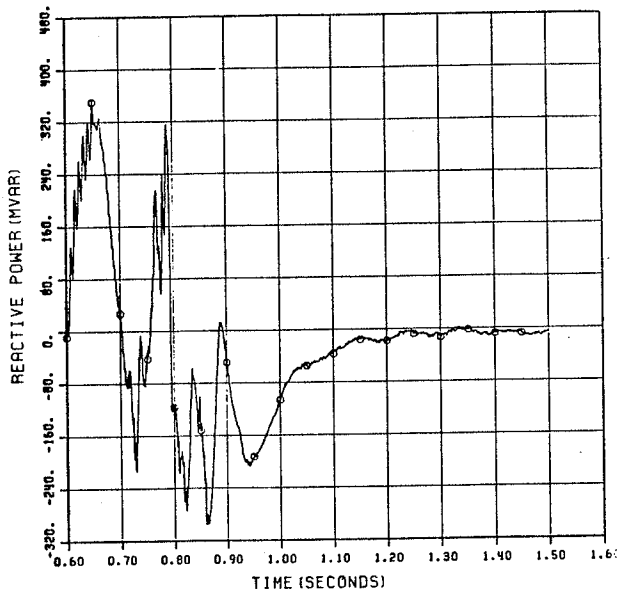
Figure 3.4: Various waveforms during a three phase ac fault  
 a - Current order,  
 b - Alpha order at the inverter,  
 c - Measured ac rms voltage (line to line)



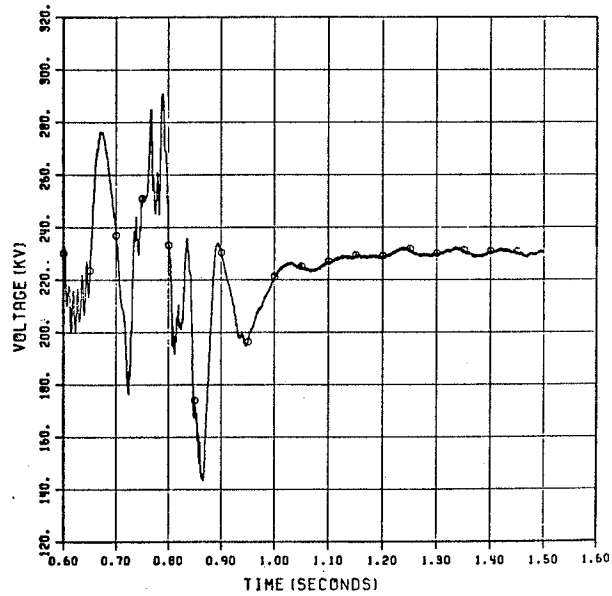
a



b



c



d

Figure 3.5: Various waveforms during a single phase fault

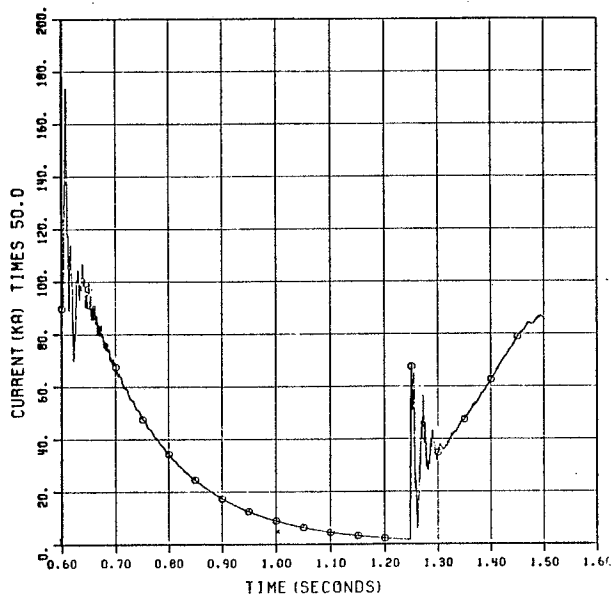
- a - Phase voltage waveform at the commutating busbar,
- b - Alpha order at the inverter,
- c - Inverter end reactive power into ac system,
- d - Measured ac rms voltage (line to line)

A dc line fault is more severe than the ac faults. A fault on the line side of the smoothing reactor at the inverter end is studied which is the most severe dc fault for a forced commutated inverter. When the fault is detected, the inverter end alpha order is set to its fault level. In order to clear the line, the rectifier is forced retarded. After the current is extinguished, the system is started again. Some of the waveforms are given in Fig.3.6. The ac voltage shows an increase as is seen in Fig.3.6-d during the dc fault. This is due to the fact that before the fault occurred, the inverter was operating at such a delay angle that it was drawing the whole reactive power produced by the ac filters. When the fault occurred since the inverter valve group is blocked, it is this reactive power flowing into the ac system that raises the ac bus-bar voltage. Fig.3.6-c shows the reactive power to the ac system from the commutating bus-bar.

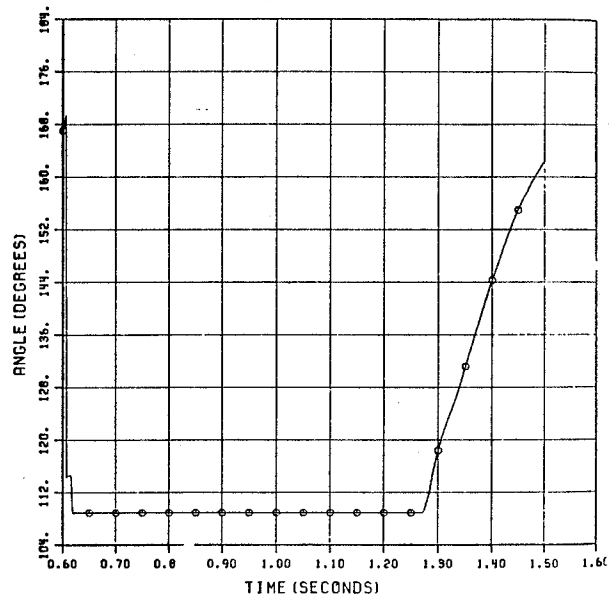
### 3.6 COMPARISON OF VALVE STRESSES

In order to compare the stresses on the valves, the studies are performed on two similar systems :

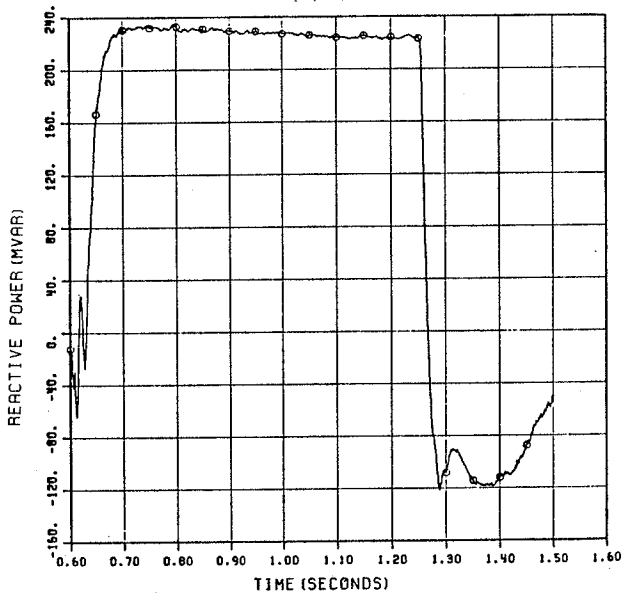
- i) Bipole 1 system with a naturally commutated inverter at the receiving end. The S.C.R. of the ac system being 3.0 pu which is the weakest system into which inversion can take place successfully. The inverter was under C.E.A. control with a gamma of  $18^\circ$  . Rated power is being transmitted.



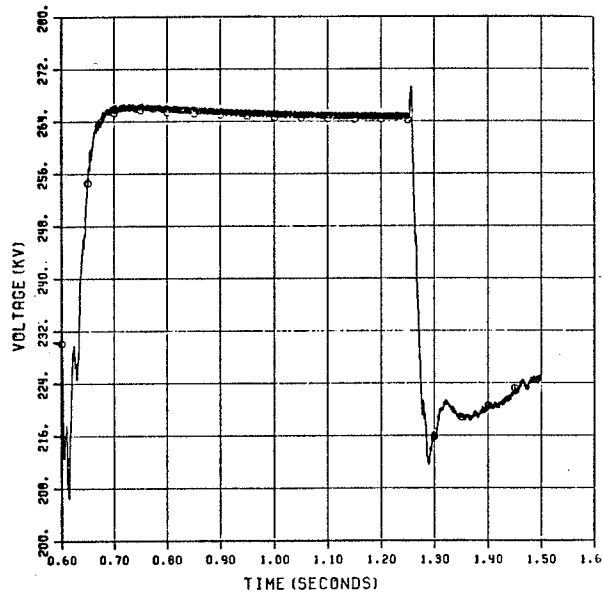
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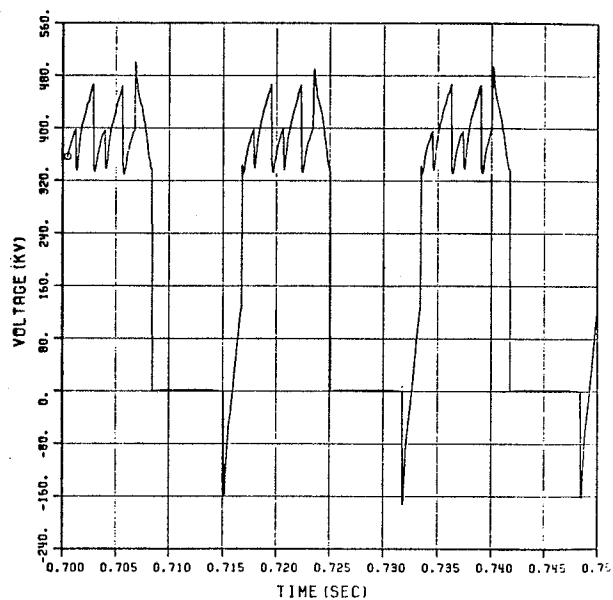
Figure 3.6: Various waveforms during a dc line fault  
 a - Measured dc current,  
 b - Alpha order at the inverter,  
 c - Inverter end reactive power into ac system,  
 d - Measured ac rms voltage (line to line)

ii) The above described system with a forced commutated inverter which includes 0.9 pu commutation capacitors between the secondary of the transformer and the valve group. The S.C.R. of the ac receiving system has been reduced to 1.0 pu for this section. The inverter is supplying the rated power and controlling the ac system voltage.

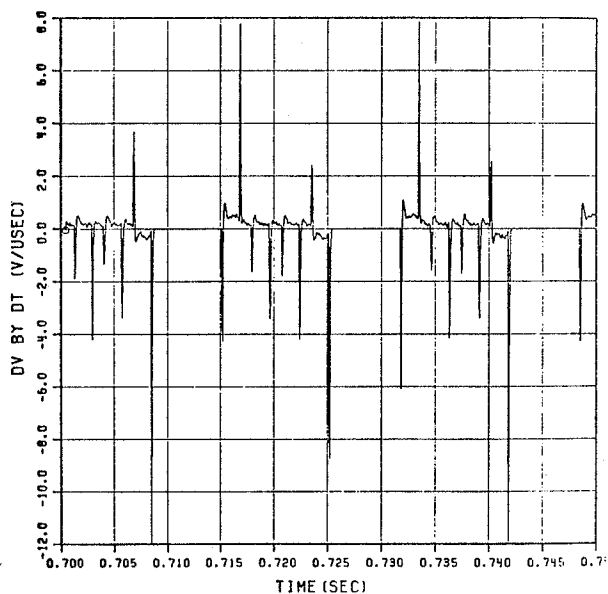
### 3.6.1 Voltage Stresses

The waveforms related to the valve stresses for naturally commutated and forced commutated inverters are given in Fig.3.7 and Fig.3.8, respectively. The ratio of forward to reverse voltage peak values between natural and forced commutated systems could be used to define the valve stresses.

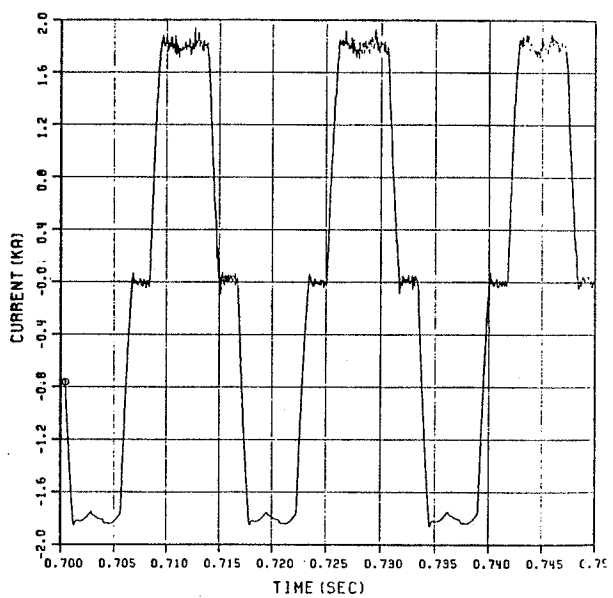
Referring to Fig.3.7-a and Fig.3.8-a, the peak forward voltage across the valve is 60 % more in the forced commutated case. The peak reverse voltages are less than the peak forward voltages in both cases. It should be remembered that the percentage given here is effective only at a certain operating point. (The valve stresses and their effects on cost will be discussed further in the economic analysis section.) It can be concluded that, forced commutation increases the number of thyristors in each bridge arm, although it eliminates the requirement of reactive power support at the ac bus-bar.



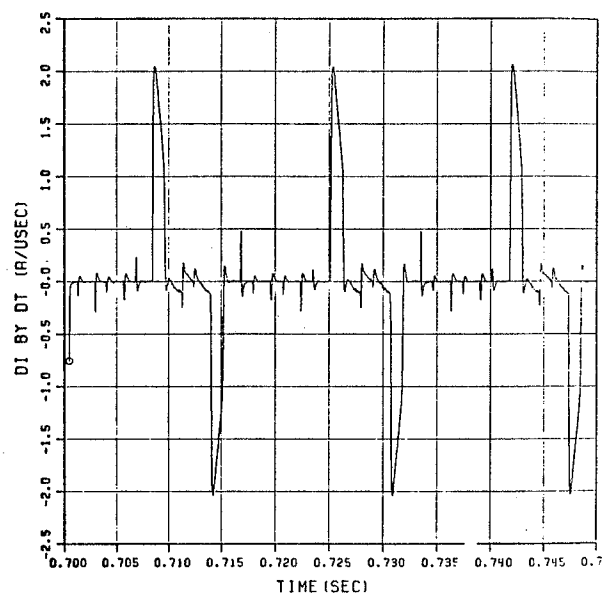
a



b



c



d

Figure 3.7: Valve stresses - Natural commutation  
 a - Voltage across the valve,  
 b -  $Dv$  by  $dt$  across the valve,  
 c - Line current on secondary side,  
 d -  $Di$  by  $dt$  through the valve.

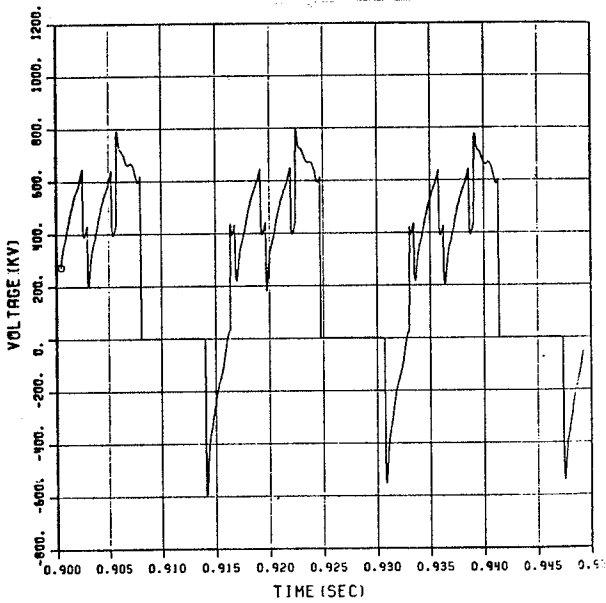
If Fig.3.7-b and Fig.3.8-b are examined, it is possible to conclude also that forced commutation increases the  $dV/dt$  (rate of change of voltage across the valve) by a ratio of 2.0 both in forward and reverse directions. It should be noted that snubber circuits are provided across each thyristor in the model and therefore the  $dV/dt$  stresses are only indicative for both cases. As  $dV/dt$  is very small in both cases changes to the snubber circuits should not be required.

### 3.6.2 Current Stresses

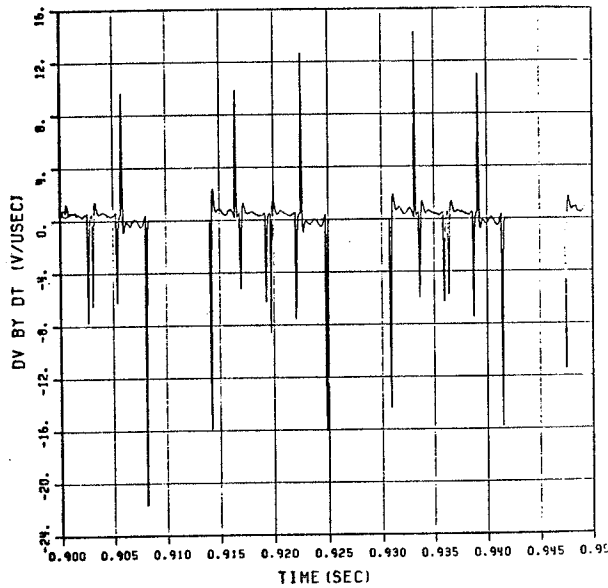
For the forced commutated inverter studied in this thesis, the rms current through the valve and transformer windings will be the same as the current in natural commutated inverter because the dc current is the same in both cases.

$$I_{RMS} = \frac{\sqrt{2}}{\sqrt{3}} I_d$$

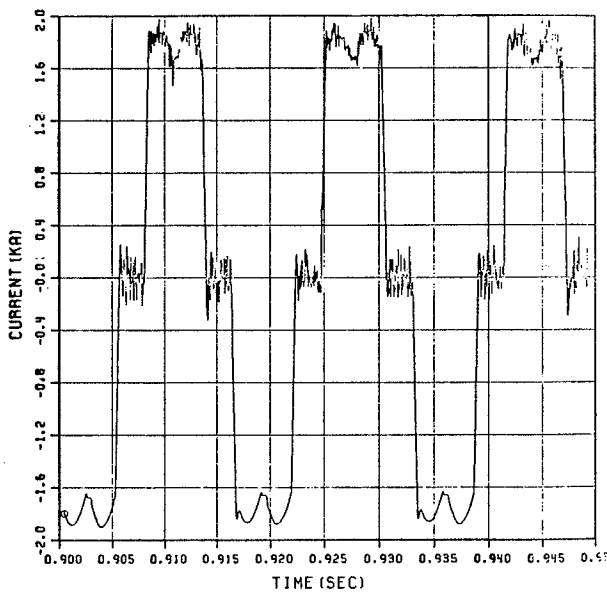
But the rate of change of current in forced commutation is greater than that in natural commutation (Fig.3.7-d and Fig.3.8-d). Even over the range for which a naturally commutated inverter is able to operate, the rate of change of current is increased with forced commutation. The ratio of maximum  $di/dt$  in forced and natural commutation is about two to one, but again the value of  $di/dt$  is well within the ratings for power thyristors.



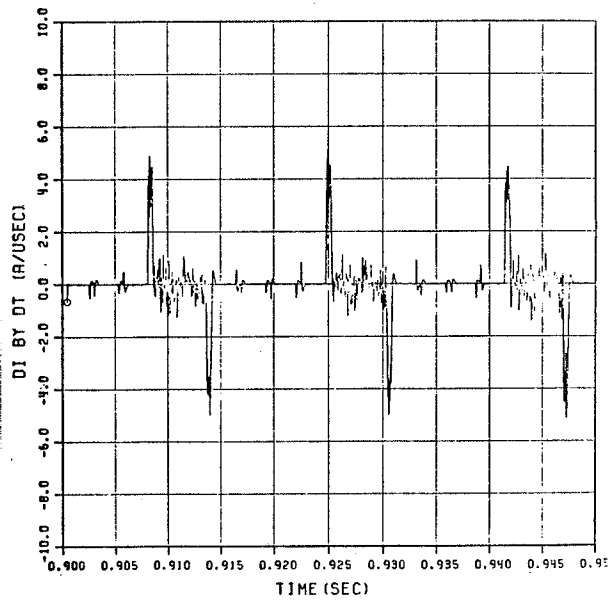
a



b



c



d

Figure 3.8: Valve stresses - Forced commutation  
 a - Voltage across the valve,  
 b -  $Dv$  by  $dt$  across the valve,  
 c - Line current on secondary side,  
 d -  $Di$  by  $dt$  through the valve.

### 3.7 AN APPROACH FOR AN ECONOMICAL ASSESSMENT OF "BIPOLE 1 SYSTEM"

In general, the considerations to estimate the cost of a transmission system are terminal and line costs including losses, power transmission capability, reliability, availability and control dynamics. The inverter, either conventional or forced commutated, might have quite a large influence on many of the above listed items.

In the preceding sections of this chapter, the performance of a forced commutated inverter has been simulated. As concluded, forced commutation is technically feasible especially when inverting into extremely weak ac systems. Certainly, before such a scheme could be considered, a fully detailed economical analysis should be performed. As a result of such an assessment, it would be possible to determine the complete feasibility of the forced commutation application compared with a conventional scheme. However, such a study would certainly need the complete and detailed design of the particular project.

The following estimate, with its inherent shortcomings, is included to provide an initial starting point for more appropriate economical analyses and to indicate that such a new technology deserves further detailed studies by manufacturers and utilities.

"In attempting to identify the costs associated with HVDC, one finds little published data. Further, what one does find is usually so heavily encumbered by qualifiers as

to be of questionable value." state Long and Lasseter {23}. This analysis is conducted on a comparison basis with the existing naturally commutated schemes. Because, it is very difficult to perform an independent cost analysis for such a new technology, only relative costs of that equipment which has a different rating, such as valves, or which is a requirement of the forced commutation, such as commutation capacitors, will be evaluated. Research expenses, special problems which might arise during the development stages will not be considered. Similarly, the cost of switch yards (ac and dc sides), signal processing, control, protection and telecommunication will be estimated from the existing HVDC systems.

For comparison with naturally commutated HVDC systems, the size and parameters of an existing dc link are used. Both the naturally and forced commutated inverters are based on a model for which the following data and basic assumptions apply :

- $V_d = \pm 450$  kV,
- $I_d = 1800$  A,
- $P_d = 1620$  MW,
- 3 bridges per pole, six-pulse operation,
- Inverter connected to 230 kV three phase network,
- Thyristor valves are air insulated and water cooled, installed indoors.

To obtain an estimate of the equipment costs involved in a naturally commutated inverter, some personal correspondence has been conducted with different HVDC manufacturers. Response has been received from three of them, namely ASEA, BBC Brown, Boveri & Cie AG and Toshiba of Japan for which results have been compiled and presented in Table 3.1 along with those from a paper {17} and a recent dissertation {24} from West Germany. As can be seen from the table, for certain items on the list there is a large range of percentages from one source to the other. This could be due to the different size of the projects for which the figures were given or due to a wide range of installation costs. Hence, the size of the plants are given in the table as well as \$/kW figures indicated by some of the manufacturers. The final two columns show the author's estimate for natural and forced commutation schemes, respectively. The breakdown for natural commutation has been derived as a result of numerous contacts and calculations for Nelson River Bipole 1 and Bipole 2 Systems at Manitoba Hydro and other breakdowns mentioned above. Although synchronous condensers are almost a standard part of a naturally commutated inverter station, required to support the ac commutation voltage and to supply the reactive power, their size and rating will change from system to system and for different design criteria. Hence the percentage cost for synchronous condensers has not been included in the breakdown.

TABLE 3.1

Estimated cost comparison for "Bipole 1 System"

Equipment	RJ-MM N.C. <sup>[17]</sup>	RJ-MM F.C. <sup>[17]</sup>	MZT <sup>[25]</sup>	ASEA	Toshiba	HMT N.C.	HMT F.C.
Main Valves	0.300	0.398	0.391	0.230	0.350	0.325	0.745
Auxiliary Valves	-	0.087	-	-	-	-	-
Commutation Capacitors	-	0.128	-	-	-	-	0.230
Transformer	0.202	0.202	0.290	0.150	0.220	0.285	0.235
Smoothing Reactor	0.053	0.053	0.065	0.070	0.080	0.050	0.050
Ac Filters	0.098	0.088	0.101	0.078	0.160	0.110	0.110
Synchronous Condensers	0.148	-	not included	0.423	not included	not included	-
Ac switchyard	0.098	0.091	0.050	0.030	0.030	0.100	0.100
Dc switchyard	0.033	0.033	0.030	0.030	0.030	0.035	0.035
Control & Protection	0.050	0.050	0.040	0.0413	0.100	0.060	0.060
Auxiliary equipment	0.025	0.025	0.033	0.030	0.030	0.035	0.035
TOTAL	1.000	1.154	1.000	1.000	1.000	1.000	1.600
Ratings considered	±400 kV 1800 A 1440 MW	±400 kV 1800 A 1440 MW	±600 kV 2100 A 2500 MW	300 MW	500 MW	±450 kV 1800 A 1620 MW	±450 kV 1800 A 1620 MW
Year considered/escalated to	1982	1982	1977	1983	1983	1983	1983
\$/kW per terminal			30.0	99.0	104.8	62.5	

The studies presented in Chapter II and preceding sections show that only the ratings of the converter transformer and bridge valves will be affected by the forced commutation compared to natural commutation. The extra cost of commutating capacitors, resulting in savings on complete elimination of synchronous condensers, will be examined and discussed.

### 3.7.1 Converter Transformers

If the forced commutated inverter is designed to operate at unity power factor (i.e. neither consuming nor producing reactive power), there could be reasonable savings on the converter transformer MVA ratings. Bipole 1 converter transformers are rated at 340 MVA each. For forced commutation, the transformer ratings would be only 270 MVA for unity power factor operation. Based on the analysis given in Ref. 24 this would result in a cost savings of 16.8 % for the converter transformer. For quick reactive power modulation in the ac system, a power factor of 0.89 leading or lagging is required (i.e. each transformer being able to transfer 140 Mvars in either directions). Transformers with a rating of 300 MVA still result in a saving of 10 %.

Also for operation near unity power factor, a reduction in insulation level of about 10-15 % at the secondary (valve) side of the converter transformers will result. This arises from the fact that a power factor near unity requires a lower ideal no-load direct voltage,  $V_{d0}$ .

### 3.7.2 Valves

Although the number of valves used in the series capacitor commutation scheme is exactly the same as the conventional bridge, the valves are subject to higher stresses in both the forward and reverse directions. Referring to Fig.2.4 in Chapter II, the extra stresses in both directions over the entire range of operation with forced commutation are about 2.3 times greater than that of natural commutation. In order to increase the voltage capability of the valves, the number of thyristors in each bridge arm is to be increased by the given ratio compared to natural commutation. Although the insulation level of the extra thyristors will be higher than those of the naturally commutated inverter, as an approximation the cost increase will be almost linear and simply 2.3 times more. Of course, if the range of the delay angle is limited to say less than  $200^\circ$ , or the permissible range of  $I_d$  is limited, then the valve stresses could be considerably reduced.

The overlap duration is shorter than that of natural commutation with the contribution of capacitor voltages to commutating voltage depending upon the delay angle. Hence the available time for de-ionization of the valves is even longer with forced commutation. Therefore in all valves, thyristors for network duty can be used. However, as a consequence of shorter overlap durations, the rate of change of current through the valves would be slightly higher which

might result in larger  $di/dt$  protection inductances in series with the thyristors.

With the water cooled thyristor valve technology, the total losses of the inverter station is reduced to about 1 % of the total power transmitted {23}. The valves together with the damping circuit contribute one third of these losses which might increase slightly with forced commutation due to higher valve stresses.

### 3.7.3 Commutating Capacitors

The series commutation capacitors and their associated protection on the secondary side of the converter transformers are the other extra cost introduced by forced commutation. As was shown in detail in Reference 21, the MVA rating of the series capacitors is almost equal to the reactive power required by the naturally commutated inverter which is usually supplied by the synchronous condensers. The MVA rating of the capacitors for the "forced commutated Bipole 1 Scheme" is about 966 Mvars per pole. (It should be remembered that the forced commutated inverter has the capability of supplying about 450 Mvars into the ac system {21}.) The unit cost of series capacitors varies over quite a large range depending upon the supplier. The unit cost per kvar is \$3.5 US by Kimbark (1971 \$), \$5.0 by ASEA (1983 \$) and \$20.1 (installed) by Manitoba Hydro (1980 \$, the equipment is only \$11.0). The unit cost given by Manitoba Hydro could

be slightly high, since this was the figure used for series compensation of 500 kV ac lines. Considering a moderate rate of \$15.0, the relative cost of capacitors would be around 23 % of the total cost of the above mentioned naturally commutated inverter station. (The total cost of the naturally commutated inverter station is calculated using a \$/kW per terminal figure of \$78.2 {26}.)

#### 3.7.4 Synchronous Condensers

In Section 3.2.1, the difficulties and problems which might be caused by a naturally commutated inverter supplying a weak ac system were described. For an acceptable and reliable operation, an S.C.R. of about 3.0 pu is usually recommended {22,27}. It has been also shown in previous sections that the forced commutated inverter can successfully operate and safely recover from anticipated faults on an extremely weak system having an S.C.R. of 1.0 pu to 1.5 pu. In order to increase the system strength to 3.0 pu the additional short circuit capacity (S.C.C.) is about 2430 MVA for the Bipole 1 System. Hence, three synchronous condensers with ratings of about 160 MVA (similar to those already used in Bipole 1 at Dorsey +160 Mvars, -80 Mvars,  $x'_d = 19\%$  on its own base) should be added to the system. Each would cost about \$10.5 million (1983 \$) {28} which is about 25 % of the above mentioned conventional system. Consideration must also be given to the maintenance and repair expenses of

these rotating machines, which are quite high compared with static equipment.

### 3.7.5 General

As can be concluded from Table 3.1 and the above discussion, the total cost of a forced commutated inverter appears to be 60 % more compared with the cost of a naturally commutated inverter. But it should be remembered that the natural commutation estimate excludes the cost of synchronous condensers. Also, maintenance, reliability and improvements in performance are in favour of the forced commutated systems {17}.

The valve expenses constitute a large portion of the forced commutation expenditures. Certainly, the cost of dc equipment has escalated significantly less than that ac equipment over the past decade {23,29}. This might have the same tendency to continue in the future hence favouring forced commutation. However, the improvements in the design of converter stations, such as reducing the commutation reactance as planned by some manufacturers, might still be in favour of conventional schemes.

### 3.8 CONCLUSIONS

The inverter is able to operate into the ac system at a delay angle close to or even beyond  $180^\circ$  which is not attainable with natural commutation. The unity power factor operation eliminates the reactive power requirement (usually about 60 % of the real power) at the ac bus-bar supplied conventionally by synchronous condensers or static VAR supplies. It has been demonstrated that it is even possible to supply reactive power from the forced commutated inverter into the ac system though the total MVA rating of series commutating capacitors is nearly equal to MVA rating of the shunt ac capacitors for operation at the same power factor. When the forced commutated inverter is designed to operate at unity power factor, only the real power will be transferred by the converter transformer. This reduces the MVA rating of the transformer by about 15-20 %.

The forced commutated inverter is found to be immune to ac side faults at the inverter ac bus-bar. The system can quickly recover from dc line faults provided that the fault is not permanent.

The forced commutated inverter introduces extra stresses on the valves. But the additional cost of the inverter due to higher valve stresses and the series commutation capacitors may well be compensated by the elimination of synchronous machines required for a natural or line commutated inverter.

The range of permitted firing angle cannot be increased beyond a certain angle for a given capacitor value and dc current. It is possible to increase the operating range by a reduction in the value of the series commutation capacitors. As the value of the capacitor decreases, the voltage which builds up across the capacitors will be higher for a given dc current. But this will result in increased valve stresses though the operating range is increased.

For application such as Bipole 1 of Nelson River HVDC System feeding into a 1.5 pu S.C.R. ac system, the estimated cost of using a forced commutated inverter is 28 % more as compared to a naturally commutated inverter.

## Chapter IV

### DC TRANSMISSION TO REMOTE LOADS

#### 4.1 INTRODUCTION

In previous chapters it has been shown that a forced commutated inverter could be used to meet the reactive power requirement at the converter terminals. This investigation is a further technical appraisal involving a two terminal transmission scheme to a remote load with little or no ac generation at the load. Several possible inverter configurations are discussed.

An electromagnetic transients program is used to model the system and simulate various aspects such as start-up, ac and dc side faults and speed of response to voltage and frequency controls. The results are covered in a paper {30} and complete results of this study are included in a technical report {31}.

The results indicate that such a scheme is indeed technically feasible and may be quite attractive from both an economic and a reliability point of view.

#### 4.2 WHY FORCED COMMUTATION FOR CHURCHILL ?

There are many remote loads far from the ac network in Manitoba currently being supplied by diesel generation. As the loads grow, the desirability of connecting these loads to the ac system increases. One such remote load is the town of Churchill, a projected 25 MW load located on Hudson Bay 260 km north-east of Heday, the northern terminal of the Nelson River Bipole 2 HVDC transmission system. Churchill is a small town which has a present electric load less than 6 megawatts. Currently the load is supplied by 9 diesel electric generating units assigned to Churchill. The total capability of generators is about 12-13 MW. To supply the growing load from the central electric system, the required transmission line length is about 260-310 kilometers. Although the load is not large enough for such a connection, the economics of supplying the load from the central electrical system rather than by diesel electric generators were studied and possible alternatives are reviewed at Manitoba Hydro from time to time. Recently, because of the increase in the diesel fuel oil costs, central system connection alternatives look quite promising {32}.

Neither the transmission distance nor the power to be transmitted can be regarded as advantageous for dc transmission. Because of the nature of the load and the following reasons, dc transmission might still be an alternative. Some of the existing constraints which tend to favour dc transmission are :

- i) The transmission line construction costs for a monopolar line at relatively low voltage are cheaper than a three-phase line because the tower construction is much simpler in dc.
- ii) The transmission line losses are less in a monopolar or bipolar scheme than in a three phase ac line. The losses will be even less in the case of a monopolar system with ground/sea return.
- iii) The rectifier station can be constructed in the collector system at Henday and use the existing dc collector system including the filters and earth electrode with a transmission line length of 260 kilometers. An ac line should be terminated outside the dc collector system at Radisson with a transmission length of 310 kilometers because of some potential problems such as unacceptable voltage oscillations, unacceptable frequency variations and complex resonances of the filters in the dc collector system at Henday.
- iv) An ac line must operate at a higher voltage level than that of a dc line for the same conductor size. Therefore, considerable savings can be achieved using a lower voltage with a dc transmission line.
- v) An ac line might need reactive power compensation, because the line is quite long. This would further increase the construction costs of the line.

vi) The capacity of the transmission system can be increased in stages as the load grows.

For a naturally commutated inverter, an alternating voltage source is required at the load end in order to commutate the valves. There is no such a source at the Churchill site except the diesel generating units. It might be possible to utilize the existing diesel generators as synchronous condensers and to provide the commutating voltage. This would require uncoupling the generator from the engine in order to save fuel. But this is not possible because all the generators are the single bearing type with the bearing at the outboard end {33}. The engine supports the opposite end of the rotor by the coupling. Running the engines to generate reactive power would not be beneficial because of fuel and maintenance costs, manning the plants and carbonning up the engines.

Unlike the naturally commutated inverter which uses the ac line to line voltage to commutate from one thyristor valve to the next, the forced commutated inverter uses a supplementary voltage source, usually by charging capacitors, to commutate the thyristor valves. Consequently the presence of an ac system voltage is no longer required to ensure successful commutation. Also with forced commutation, operation of a bridge in all four quadrants is possible and hence reactive as well as real power may be supplied to the load. The forced commutated inverter therefore seems

particularly suited for inverting into an ac system which may not have adequate voltage support.

#### 4.3 MODELLING AND SIMULATION

The Manitoba Hydro electromagnetic transients program EMTDC {18} is used to model and simulate the systems. The monopolar transmission line is simulated by a distributed transmission line model with frequency dependency included to ensure representative damping of line transients.

Normal 11th, 13th and high pass (HP) ac harmonic filters (LC) as well as 5th and 7th filters were connected to the remote load commutation bus. A conventional rectifier feeds the monopolar line and forced commutated inverter. A simple passive load with inductive and resistive components is represented at the inverter commutating bus with the option to include an induction motor for dynamic load effects. The induction motor is modelled using the conventional two axis representation. Each valve is individually modelled with an equivalent resistor - capacitor (RC) valve damping circuit. For each valve group, valve firing is simulated with resistor switching controlled by timing pulses which are phase adjusted relative to an oscillator by the ordered firing angle ( $\alpha$  order). The oscillator may be phase locked to the ac system voltage on the commutating bus for naturally commutated converters. Alternatively, the oscillator is controlled from an independent clock if the converter is forced

to commutate into a dead load or provide the only source of ac system frequency control. At the rectifier, the firing control is derived from a conventional phase locked oscillator to control dc current as is normal with most HVDC rectifier applications.

#### 4.4 POSSIBLE SYSTEM CONFIGURATIONS

Three basic system configurations will be discussed; each consists of a dedicated controlled rectifier at Henday, the sending end and a monopolar 75 kV dc transmission line to Churchill. All systems operate in steady-state in essentially the same way. The main differences in the systems are the way in which the system is started and the method of controlling the receiving end ac voltage.

Each system configuration will be described briefly and some results of the simulation will be presented for each configuration.

##### 4.4.1 System A

The first configuration, System A, is shown in Fig.4.1 where all the system data are given in Appendix C. The receiving end system consists of a single six-pulse series capacitor commutated inverter, a load consisting of R and L elements and the existing diesel generators.

The start-up procedure begins with the diesel generators supplying the load and the inverter by-pass switch closed.

The rectifier is de-blocked and the dc current is increased to 0.3 pu using a current controller at the rectifier. Now the inverter is deblocked and the by-pass switch opened. A pole controller similar to that at the rectifier is used at the inverter with a current margin setting of 0.1 pu. At this point, the commutating voltage on the capacitors is small and hence the firing angle cannot be advanced much beyond  $180^\circ$ . The rectifier current order signal is now ramped up to its nominal value of 1.0 pu and the load is now supplied by the inverter with the diesel generators on no load. The diesels may now be switched off and the inverter is the sole supply to the load. This start-up sequence requires less than one second to complete.

At the time that the diesel generators are switched off several modifications need to be made to the controls. Firstly, there is no longer an ac system reference voltage, however weak, from which the phase lock loop control (the delay angle control to maintain constant ac bus-bar voltage) may take signal. The valves now must be fired in sequence from an independent clock working at 60 Hz. Secondly, the inverter is behaving as a current source injecting an ac current proportional to the dc line current into the load. Hence the ac system voltage at the load is dependent on the magnitude of the load impedance and the ac current injected into the load. The value of firing angle,  $\alpha$ , is now irrelevant, being dependent on the power factor of the load and

the overlap angle of the inverter. The receiving end ac system voltage must now be controlled by the dc current controller at the rectifier end.

A constant voltage controller at the rectifier end takes over the control, and by changing the delay angle at the rectifier, it modifies the internal voltage, hence the dc voltage and current flowing in the line, therefore keeping the voltage at the inverter side ac bus-bar constant. The constant voltage controller at the rectifier end must receive its input from the inverter end with a communication link. This is one of the major disadvantages of this configuration as a reliable fast communication link must be maintained between the terminals of the system in order to control the ac voltage of the load.

Once started the inverter is virtually immune from ac side faults but dc side faults require blocking of the converters and repeat of the start-up procedure, including the start up of the diesel generators. This, of course is another major disadvantage of this system. The last major disadvantage of this system occurs at very light loads. The current injected into the load must be very small and as the commutating capacitors are charged by this current, they do not receive sufficient charge to overcome the ac system voltage and a commutation failure will occur. The only solution to this problem is to switch the commutating capacitors under light load conditions.

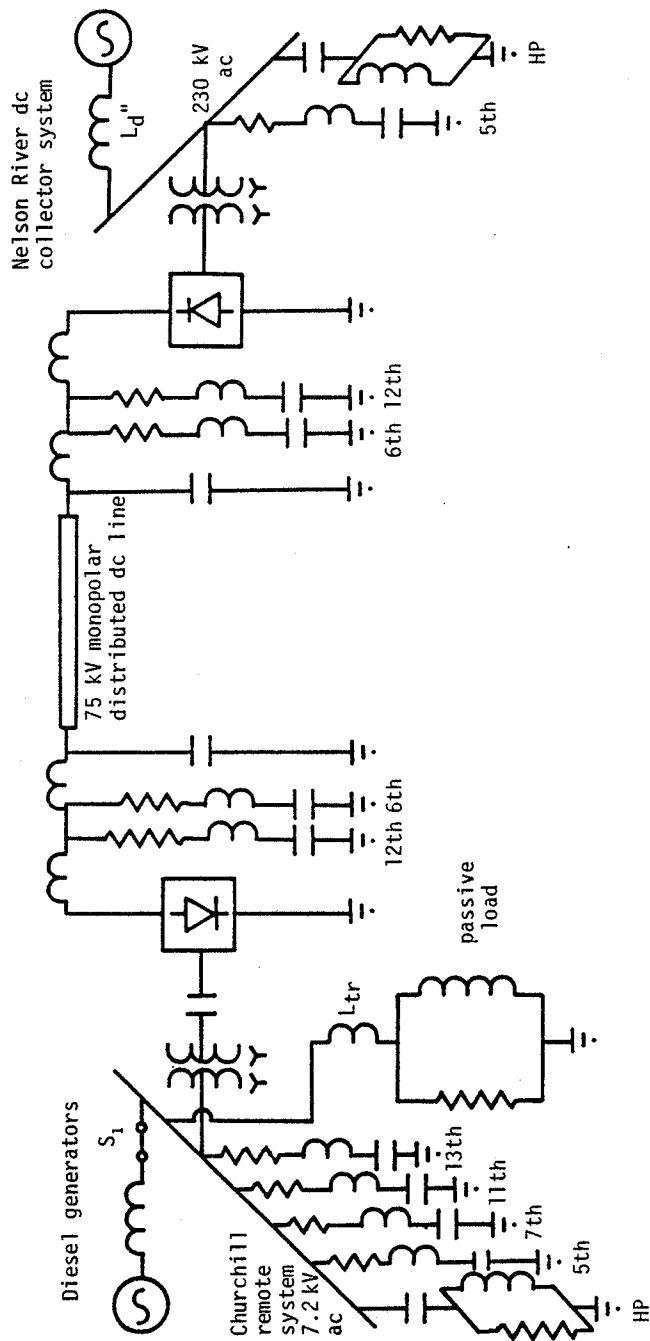


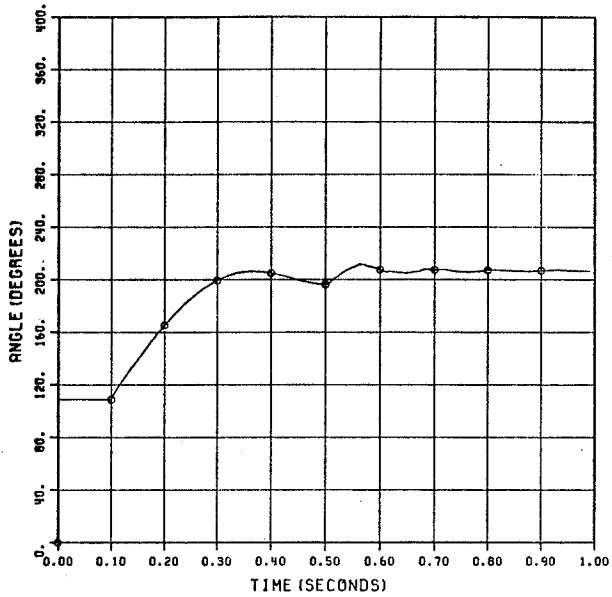
Figure 4.1: Complete model of transmission link for Systems A and B

The simulation results related with the above described start-up procedure are shown in Fig.4.2. The switch  $S_1$  is opened at current zero crossings. The oscillations in power measurements arose, because the switch  $S_1$  is modelled by a very small resistance when it is shorted. This value is very small in the impedance matrix compared to other components connected to that particular bus-bar. As it is seen from Fig.4.2-b, the complete load power is supplied by the inverter at  $t=0.5$  s. The reactive power produced by the ac shunt filters is supplying a part of the reactive power requirement of the load. The rest is being supplied by the inverter. As is seen from Fig.4.2-d, the ac voltage at the commutating bus-bar is quite closely controlled even at the moment of the isolation of the diesel units.

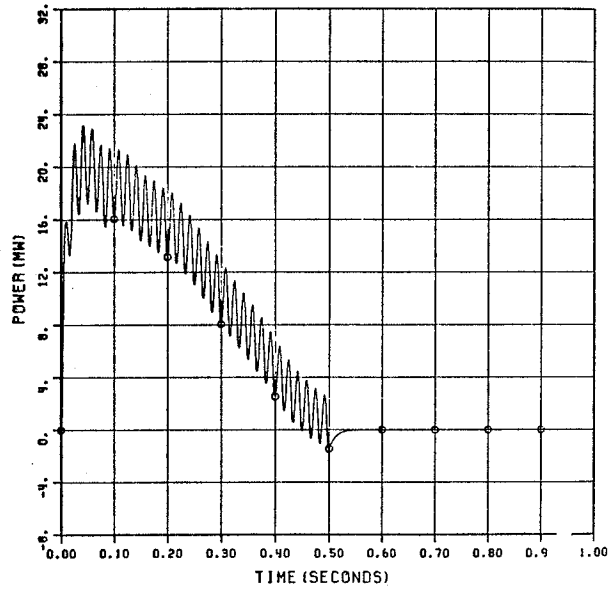
#### 4.4.2 System B

The second configuration, System B, is similar to System A except the diesel generators are not present. For a dc line fault, the inverter should be shut down and re-started. The forced commutated inverter should be able to start-up itself for a reliable operation without the support of diesel generators.

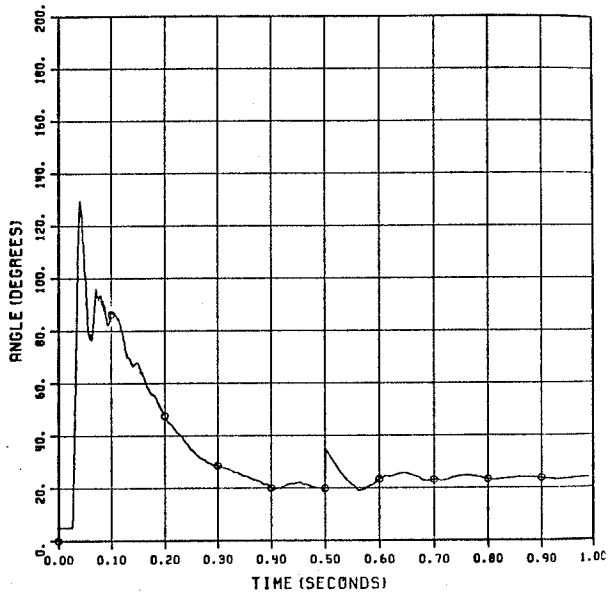
To start the system with one valve group only, the capacitors should be pre-charged using the dc current flowing in the dc line. The capacitors cannot be charged through the load, because the load has an inductance. Also the charging



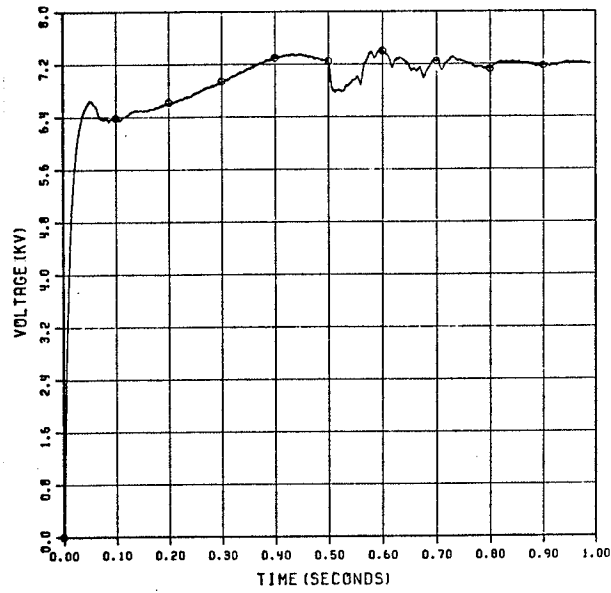
a



b



c



d

Figure 4.2: Various waveforms related with the start-up of System A

- a - Alpha order at the inverter,
- b - Real power from diesel machines,
- c - Alpha order at the rectifier,
- d - Measured ac rms voltage (line to line).

will be dependent upon the time constant of the load. For this reason, to achieve start-up of this system the ac system must be shorted. This allows the dc current to build up to a minimum operating level while ensuring adequate commutating voltages on commutating capacitors. When a sufficient voltage builds up across capacitors, the shorting switches may be opened and the ac voltage is then allowed to build up. A detailed discussion of this starting method is given in Reference 10.

There are some disadvantages of the application of this circuit :

- i) The shorting switches are an extra cost for the system. Although the switches are opened at current zero crossing, circuit breakers with suitable ratings must be installed between the phases.
- ii) The times of opening the shorting switches are very critical. During the short period of time (2.777 ms) the switch should be opened successfully. This might require sophisticated circuit breakers.
- iii) When the secondary side of the transformer is shorted, the load cannot be supplied, but it should be remembered that it is already a dead load and the dc link is the only power supply to the ac system.
- iv) It might not be possible to run the system at low loads. At lower loads, the current flowing in the

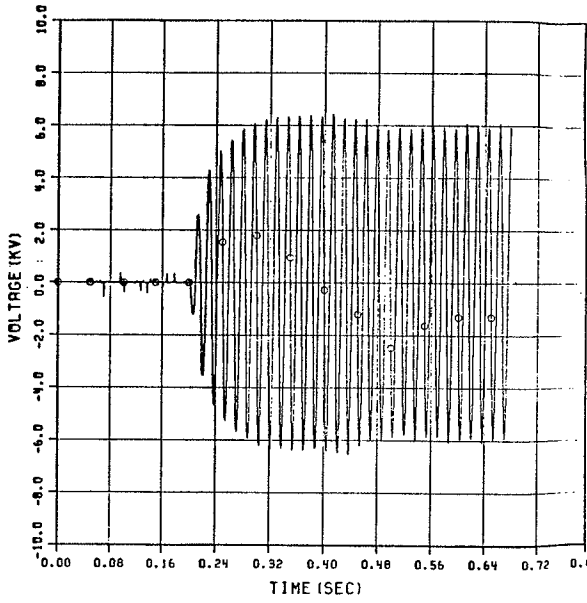
dc line will be quite small. Since the voltage across the capacitor depends directly upon the magnitude of dc current, when the current is very low, the capacitor voltage might be insufficient for commutation.

This system does eliminate the diesel generators from the system. Once started this system behaves as System A with the inherent requirements of a fast communication link to the rectifier to control the ac system voltage, and a minimum current limit before the commutation capacitors must be changed. Start up following a dc line fault can be achieved faster since only the shorting switches on the ac commutating bus need to be closed.

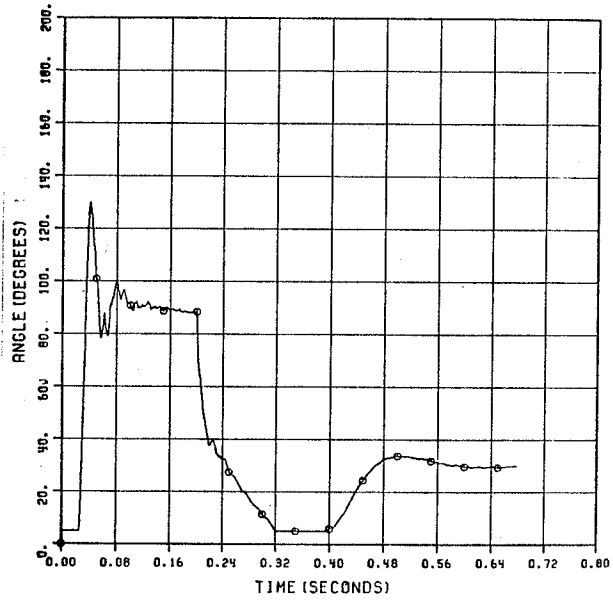
Fig.4.3 shows the start-up of the system. The ac busbar voltage at the inverter end is controlled by the rectifier end (Fig.4.3-b). The overvoltage which appears at the moment of removing the shorting switches in the ac system is acceptable (Fig.4.3-c).

#### 4.4.3 System C

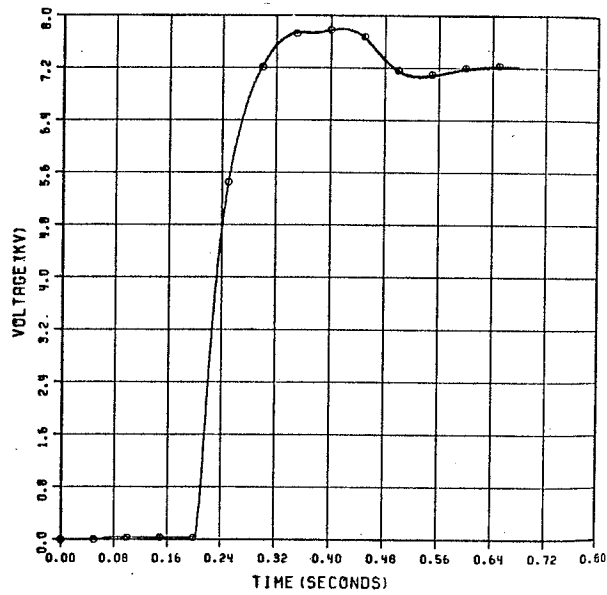
The third configuration, System C, shown in Fig.4.4 employs two six-pulse bridges in series at the receiving end. Some of the system data at the receiving end has been modified for this system (Appendix C). This system configuration alleviates the major disadvantages of the previous schemes. Diesel generators or shorting switches are not re-



a



b



c

Figure 4.3: Various waveforms related with the start-up of System B  
 a - Ac voltage at the commutating busbar,  
 b - Alpha order at the rectifier,  
 c - Measured ac rms voltage (line to line).

quired. The ac system voltage is controlled at the inverter eliminating the need for a reliable fast communication link and operation from no load to full load is possible.

#### 4.4.3.1 Controls

The controls are straight forward; the top bridge is pulsed at the fixed 60 Hz clock frequency and the lower bridge is pulsed at the same frequency only delayed by an angle  $\Delta$  degrees. This angle is the difference in the firing angle delays of the two bridges but as the firing angle,  $\alpha$ , is no longer important only the delay angle  $\Delta$  will be discussed. The current injected into the load from the ac bus is the vector sum of the currents from the two bridges and hence the load voltage may be controlled at the inverter end by controlling  $\Delta$ .

Fig.4.5 shows the arrangement of two forced commutated bridges in series and the phasor relationship of currents through the top and bottom converter transformers with respect to commutating bus-bar voltage. Bowles suggests that a combination of forced and natural commutated bridges could be used to control the ac voltage {34}, but this would severely restrict the operation of the inverter. To efficiently supply reactive power to the system both valve groups may be required to operate with delay angles  $\alpha$  beyond  $180^\circ$ . This system eliminates the need for a fast communication link to the rectifier and also allows minimum current

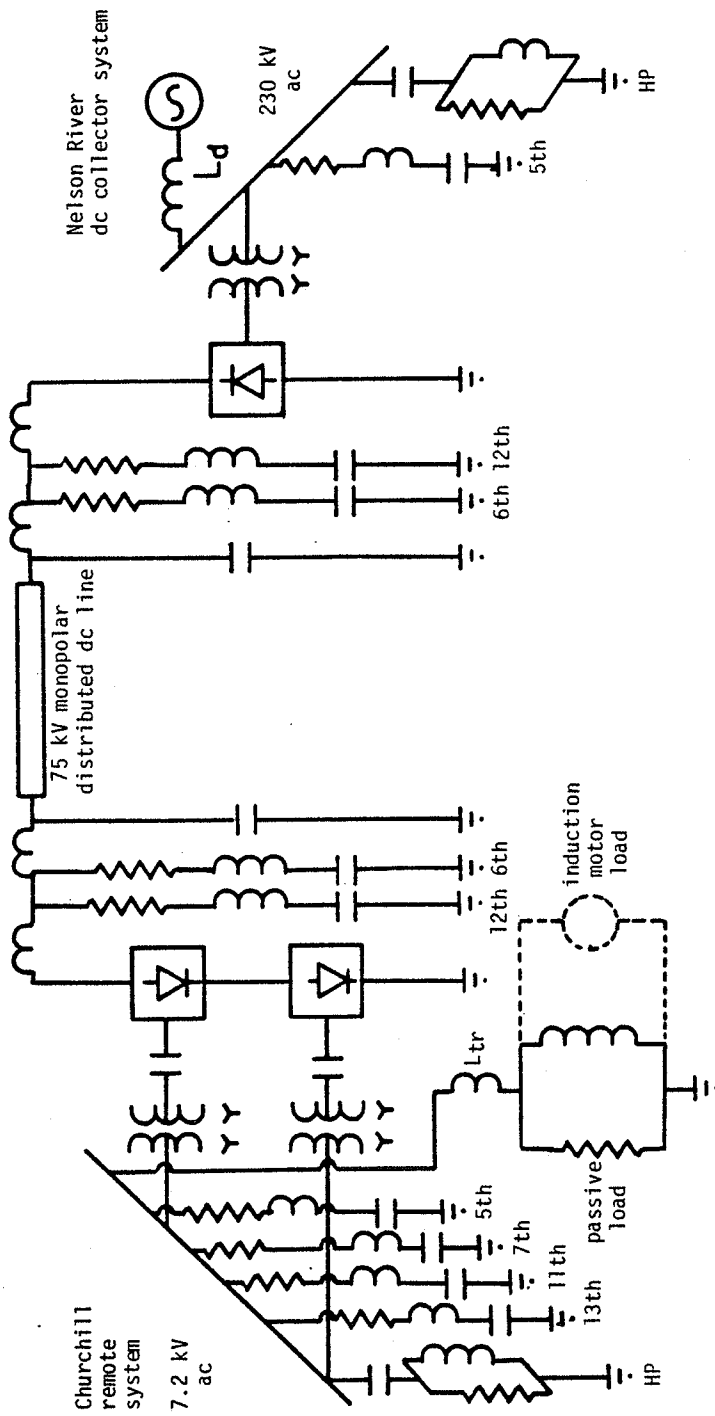


Figure 4.4: Complete model of the dc link for System C

to flow in the bridges even for the no load condition. It will be shown that  $\Delta$  may be changed by about  $20^\circ$  each commutation so that very rapid control of voltage may be achieved.

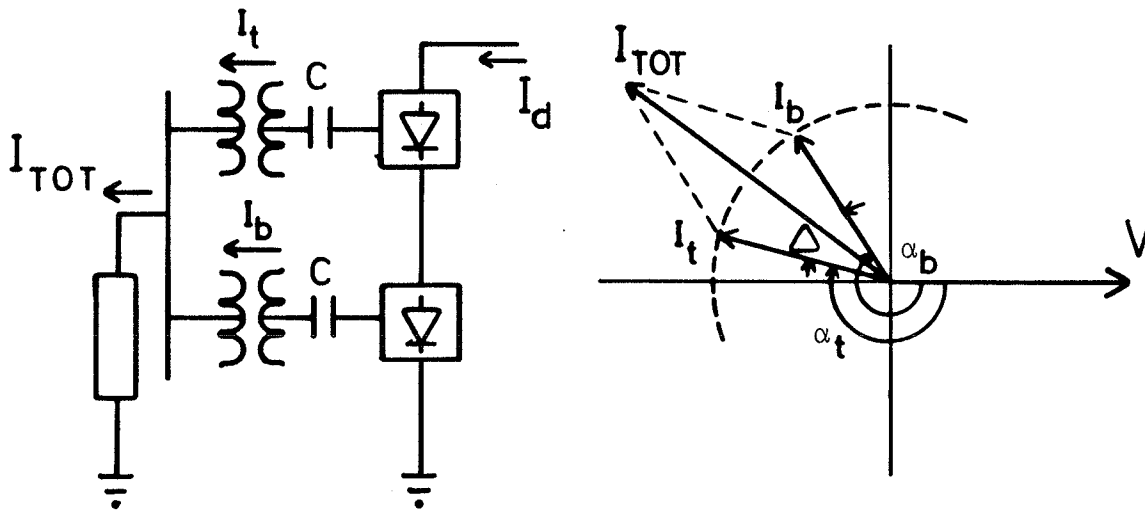


Figure 4.5: Forced commutated bridges and phasor relationship

At the forced commutated inverter, the firing control is derived from an independent clock producing exact ac frequency. Good ac voltage control is achieved through the controller shown in Fig.4.6. The difference in firing angle order ( $\Delta$ ) to the two inverter valve groups is utilized to control ac voltage provided there is sufficient current in the dc line. Current order at the rectifier is increased if in the steady state,  $\Delta$  approaches zero and becomes less

than desired level (typically  $15^\circ$ ). Conversely, if in the steady state,  $\Delta$  increases beyond  $45^\circ$ , the rectifier is ordered to reduce the dc current.  $\Delta$  may exceed these levels of 15 and 45 degrees transiently, or when allowable dc current is limited at maximum or minimum values. System loss optimization may also add constraints on the normal operating range of  $\Delta$ .

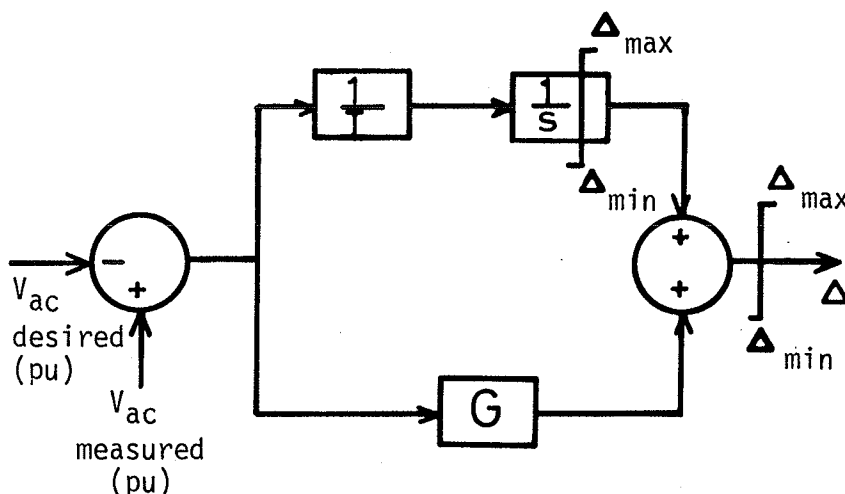


Figure 4.6: Block diagram of constant voltage controller at the inverter end

As an option, it could be possible to adjust the current order such that the forced commutated inverter operates at a certain delay angle difference  $\Delta$ . If the system is run at an operating point resulting in delay angle difference  $\Delta$  of around  $30^\circ$ , the 5th and 7th ac current harmonics and 6th dc voltage harmonic will be minimized. As well the dc line

losses will be minimized while still providing an adequate control margin on the ac system voltage during load increases.

A simple control logic has been implemented to define the current order depending upon the value of  $\Delta$ . The logic satisfies the equation :

$$I_{old} \cdot \cos\left(\frac{\Delta_m}{2}\right) = I_{new} \cdot \cos\left(\frac{\Delta_d}{2}\right)$$

where

- $I_{old}$  : present current order (pu),
- $I_{new}$  : resultant current order (pu),
- $\Delta_m$  : measured delay angle difference (degree),
- $\Delta_d$  : desired delay angle difference (degree).

The new current order  $I_{new}$  is to be transmitted to the rectifier end. This information could be sent even by a voice telephone link. In the event of a failure of the communication link the current order would be set at the upper limit and  $\Delta$  would control the voltage at the inverter. (The operation of the system with this controller will be demonstrated in the results section.)

In order to show the effect of  $\Delta$  on ac current harmonics, the 5th and 7th harmonic filters are disconnected from the system. Figure 4.7-a and b present the ac voltage waveforms, the inverter operating at deltas of  $75^\circ$  and  $30^\circ$ , respectively. The results of a Fourier analysis performed on these waveforms are presented in Table 4.1 and Table 4.2 .

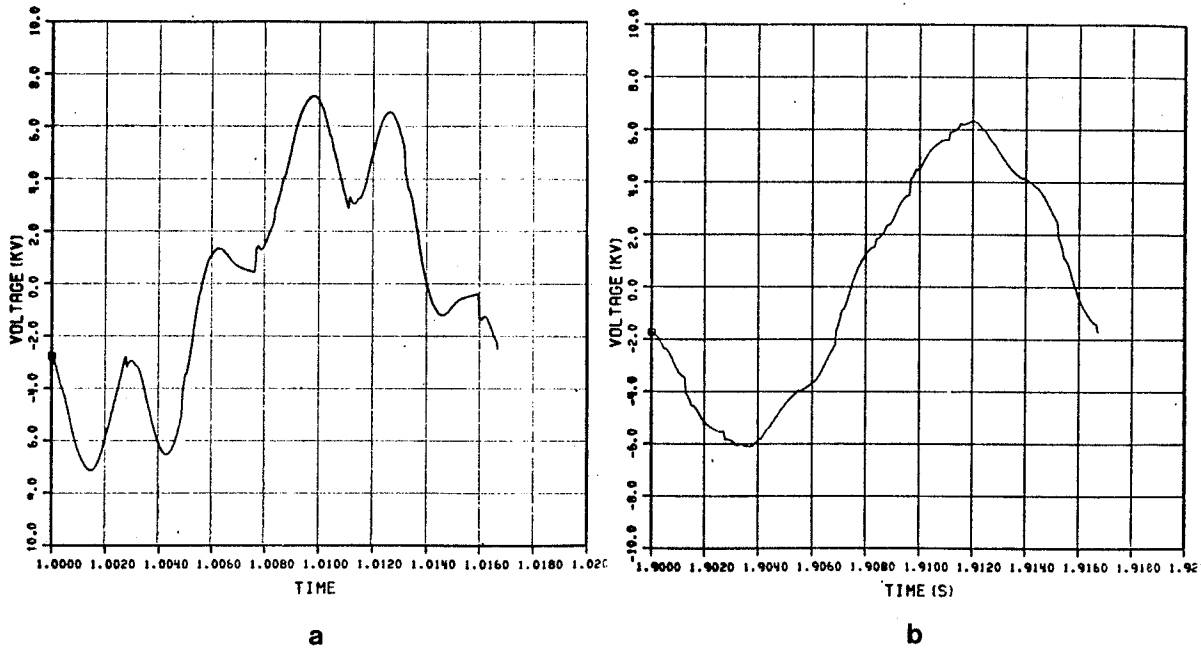


Figure 4.7: Voltage waveforms at different deltas  
 a -  $\Delta = 75^\circ$ ,  
 b -  $\Delta = 30^\circ$ .

The non-characteristic harmonics occur because of the resolution of the time step in the numerical calculations.

In a conventional point to point system, the dc fault current is deionized by applying a forced retard which is activated by line protection at the rectifier end. For simplicity, the forced retard has not been implemented with the controls. The voltage dependent current limiter with a very low fault current order level has been assigned to clear the dc line fault.

TABLE 4.1

Ac current harmonics for operation at  $\Delta = 75^\circ$ 

<u>Harmonic number</u>	<u>Harmonic distortion (pu)</u>
1	0.7736
2	0.0019
3	0.0060
4	0.0024
5	→0.2871
6	0.0052
7	→0.0746
8	0.0027
9	0.0023
10	0.0022
11	0.0024
12	0.0025
13	0.0058
14	0.0020
15	0.0022
16	0.0021
17	0.0045
18	0.0021
19	0.0066
20	0.0022
21	0.0023

#### 4.4.4 Results of System C Simulation Studies

A good test for any power system simulation is to observe the performance of the system during the start-up and steady state. The recovery from ac and dc side faults at the receiving end of the dc link is also important as far as the operation and reliability of the system is concerned.

##### 4.4.4.1 Start-up

Fig.4.8 demonstrates a one second portion of the simulation which utilizes the above described start-up procedure and dynamic controller actions. As is seen from the fig-

TABLE 4.2

Ac current harmonics for operation at  $\Delta = 30^\circ$ 

<u>Harmonic number</u>	<u>Harmonic distortion (pu)</u>
1	0.9396
2	0.0062
3	0.0048
4	0.0039
5	-0.0452
6	0.0038
7	-0.0408
8	0.0016
9	0.0014
10	0.0012
11	0.0048
12	0.0017
13	0.0028
14	0.0022
15	0.0018
16	0.0017
17	0.0029
18	0.0017
19	0.0061
20	0.0016
21	0.0020

ures, from the initialization of the system to steady-state takes about 700 ms, by which time, the inverter end ac voltage stabilizes to its set value. At time  $t=0.2$  s when the ac system is energized,  $\Delta$  is changed quite quickly (about  $20^\circ$  per commutation) without causing difficulty. The ac voltage is building up slowly because the dc current is increasing slowly during this time. At time  $t=0.45$  s, the ac voltage reaches its rated value and an overvoltage of 8 % occurs due to the sluggishness of the constant voltage controller. In the steady state, there is no distortion or spikes on the ac voltage waveform due to adequate filtering. Some spikes

during the start-up (at time  $t=0.2-0.3$  s) exist, which may be due to pre-charging of the ac shunt filters.

#### 4.4.4.2 Ac Faults

After the system reaches steady state operation a three-phase fault near the commutating bus-bar is applied. The fault occurs at  $t=1.1$  s and lasts for 3 cycles (50 ms). Fig.4.9-a shows one of the faulted phases. During the fault, voltages on all of the phases collapse to near zero. When the fault starts, dc current increases transiently since the dc voltage at the inverter end has also collapsed, but it is controlled by the rectifier end constant current controller (Fig.4.9-b). The drop on the ac bus-bar voltage is sensed by the constant voltage controller and therefore  $\Delta$  is decreased. Assuming the fault is cleared at time  $t=1.15$  s, the system voltage easily recovers and reaches steady-state in about half a second after the fault occurred.

#### 4.4.4.3 Dc Line Faults

A dc line fault is a very severe fault for a forced commutated inverter which is supplying a dead ac system. It is the dc current which charges the line capacitors in order to provide the necessary commutating voltage. Once a dc line fault occurs, the system should be blocked and re-started after an adequate de-ionization time for the fault. Fig.4.10 shows the system performance in case of a low impe-

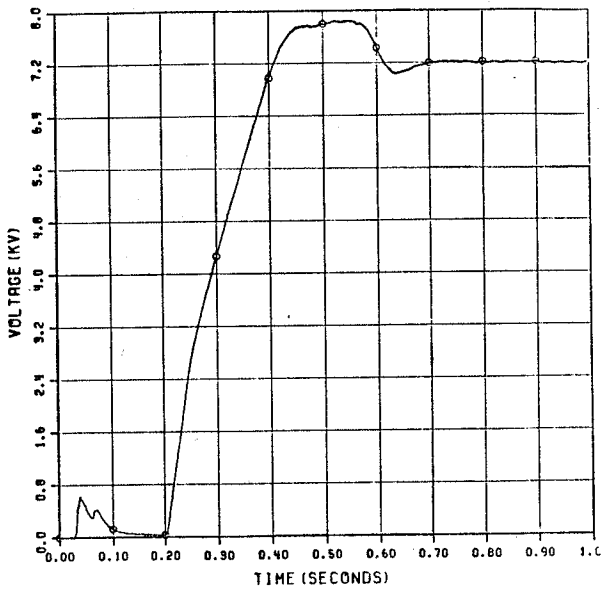
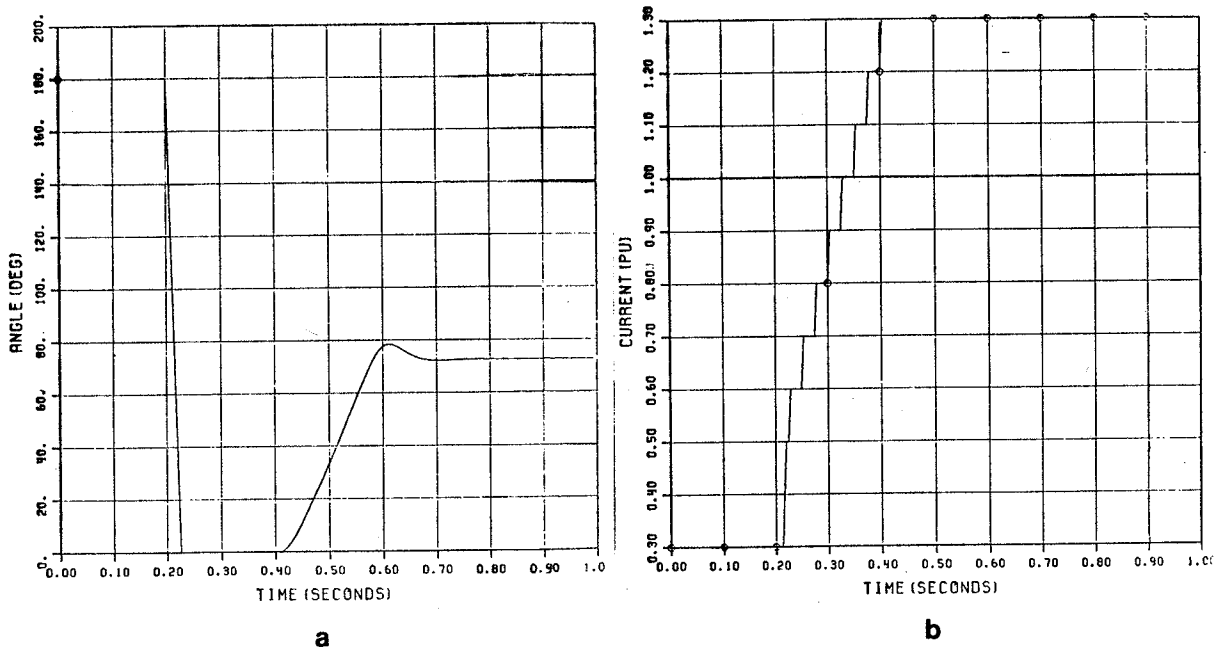
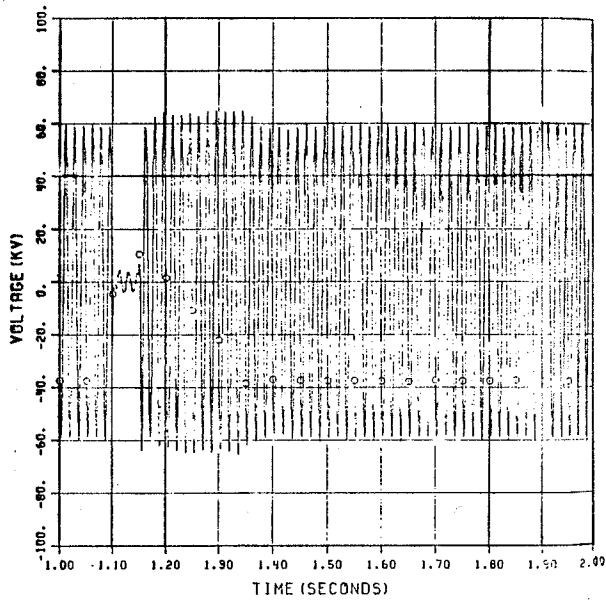
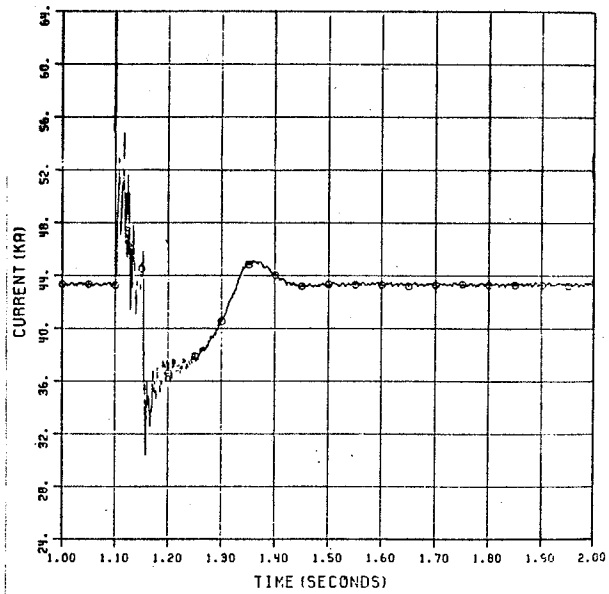


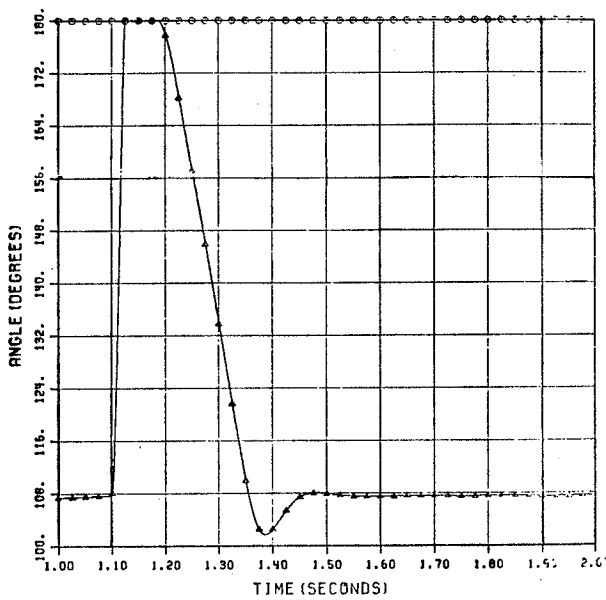
Figure 4.8: Various waveforms related with the start-up of System C  
 a - Delta,  
 b - Current order,  
 c - Measured ac rms voltage (line to line).



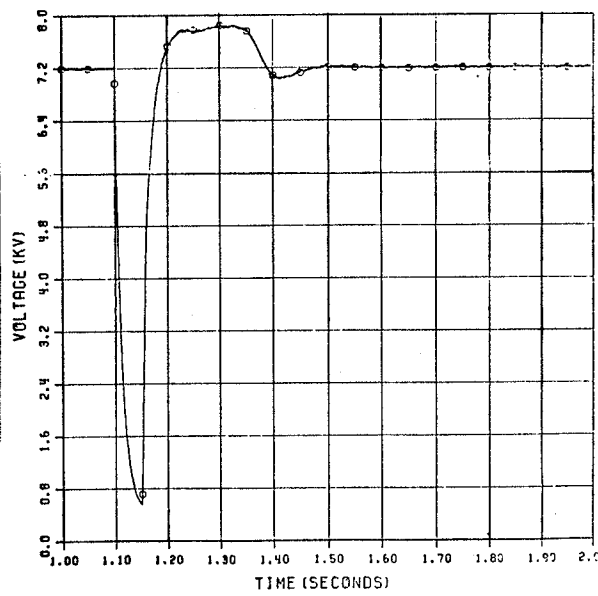
a



b

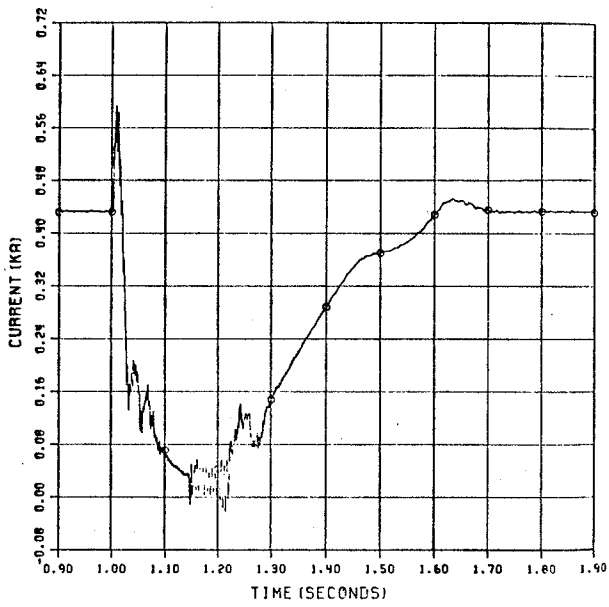


c



d

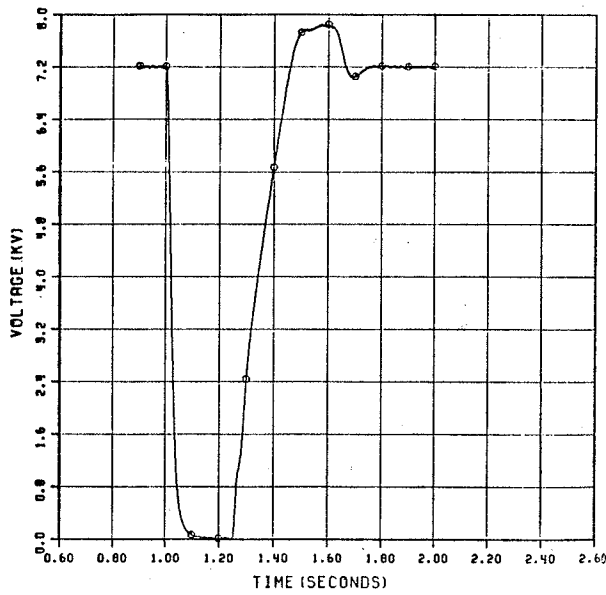
Figure 4.9: System C - Waveforms related with three phase ac fault  
 a - Ac voltage at the commutating busbar,  
 b - Dc current,  
 c - Alpha orders to valve groups,  
 d - Measured ac rms voltage (line to line).



a



b



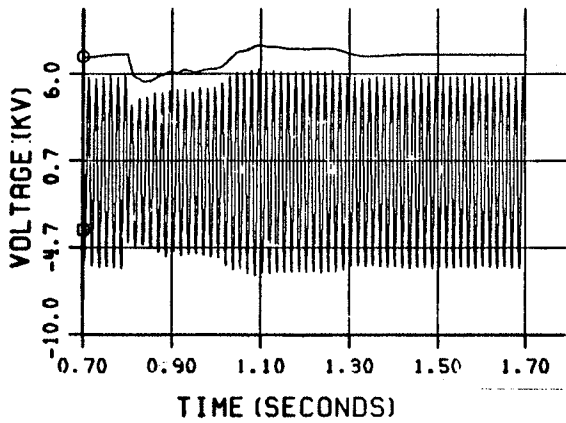
c

Figure 4.10: System C - Waveforms related with dc line fault  
 a - Dc current,  
 b - Ac voltage waveform,  
 c - Measured ac rms voltage (line to line).

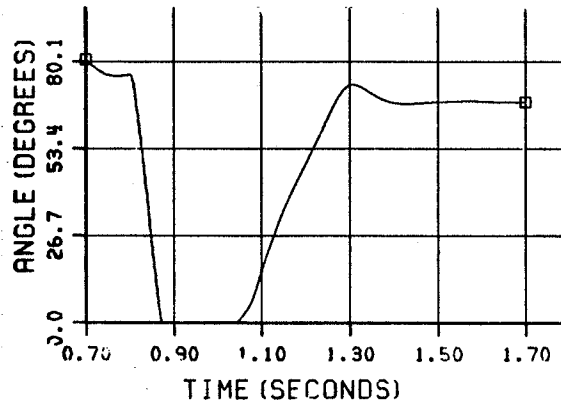
dance line-to-ground fault at the inverter end of the dc line. The fault is assumed to take place at time  $t=1.1$  s. At this time the system was operating normally. The short circuit causes a complete collapse of the voltage at the inverter side and as a result dc current increases. To limit the current, the rectifier responds and increases its delay angle, therefore decreasing the dc voltage at the rectifier end. The fault, resulting in an absolute collapse of the voltage at the inverter end, activates the rectifier voltage dependent current limiter (VDCL), after a detection delay of 12 ms, and the current order is set to its fault level. At the inverter the VDCL resets the delta angle to  $180^\circ$  in order to start up the system when the fault is cleared. Assuming the fault is cleared after 50 ms, this is sensed by the voltage dependent current limiter and the start up procedure is initiated. The same start up procedure as described before applies here, and the system recovers to its pre-fault operating point in about 0.8 s after the fault took place.

#### 4.4.4.4 Start-up of an Induction Motor

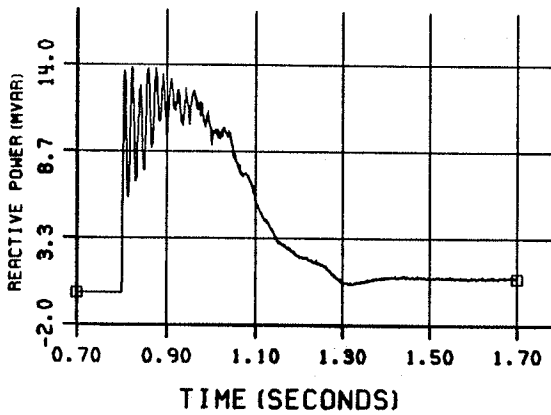
In order to illustrate the performance of the system during dynamic changes a 1.25 MW double squirrel-cage motor is direct-on-line started {35,36}. (The data for the induction motor are given in Appendix D.) With reference to Fig. 4.11, the system is in steady state supplying 23.75 MW at



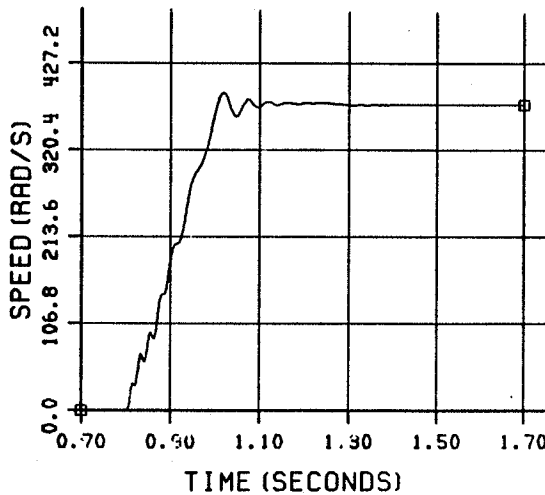
a



b



c



d

Figure 4.11: Starting of Induction Motor

- a - Ac line to line rms voltage,  
Ac line to ground voltage,
- b - Delta,
- c - Reactive power supplied to the motor,
- d - Motor rotor speed.

0.8 power factor lagging when the motor is started at 0.8 seconds. The inertia of the motor is set low in order to reduce the starting time. The load voltage drops to 5.6 kV resulting in a rapid change in  $\Delta$  to maintain the voltage close to rated value during start up. It should be noted that during this time the inverter is supplying about 12 Mvars to the motor alone. The motor reaches rated speed in about 0.2 s at which time there is a slight overvoltage and the system quickly settles with a new value of  $\Delta$ . The studies also indicated that the motor can successfully recover after the clearance of a dc line fault [31].

#### 4.4.4.5 Operation at a Desired $\Delta$

As seen from Fig.4.8, the current order is set constant at 1.3 pu resulting in a higher  $\Delta$  value of about  $75^\circ$ . Referring to Fig.4.12, the system was in steady state at 0.0 s. At this time the current order controller is activated and  $\Delta$  approaches its set value of  $30^\circ$  while maintaining the ac voltage at the commutating busbar within acceptable limits. (The current order controller makes decisions once every half a second in order to allow sufficient time for the dc current to settle.)

Since the individual delay angles of upper and lower bridges are changing as  $\Delta$  moves, real and reactive powers supplied by these groups are also changing but still maintaining the constant total powers (Fig.4.12).

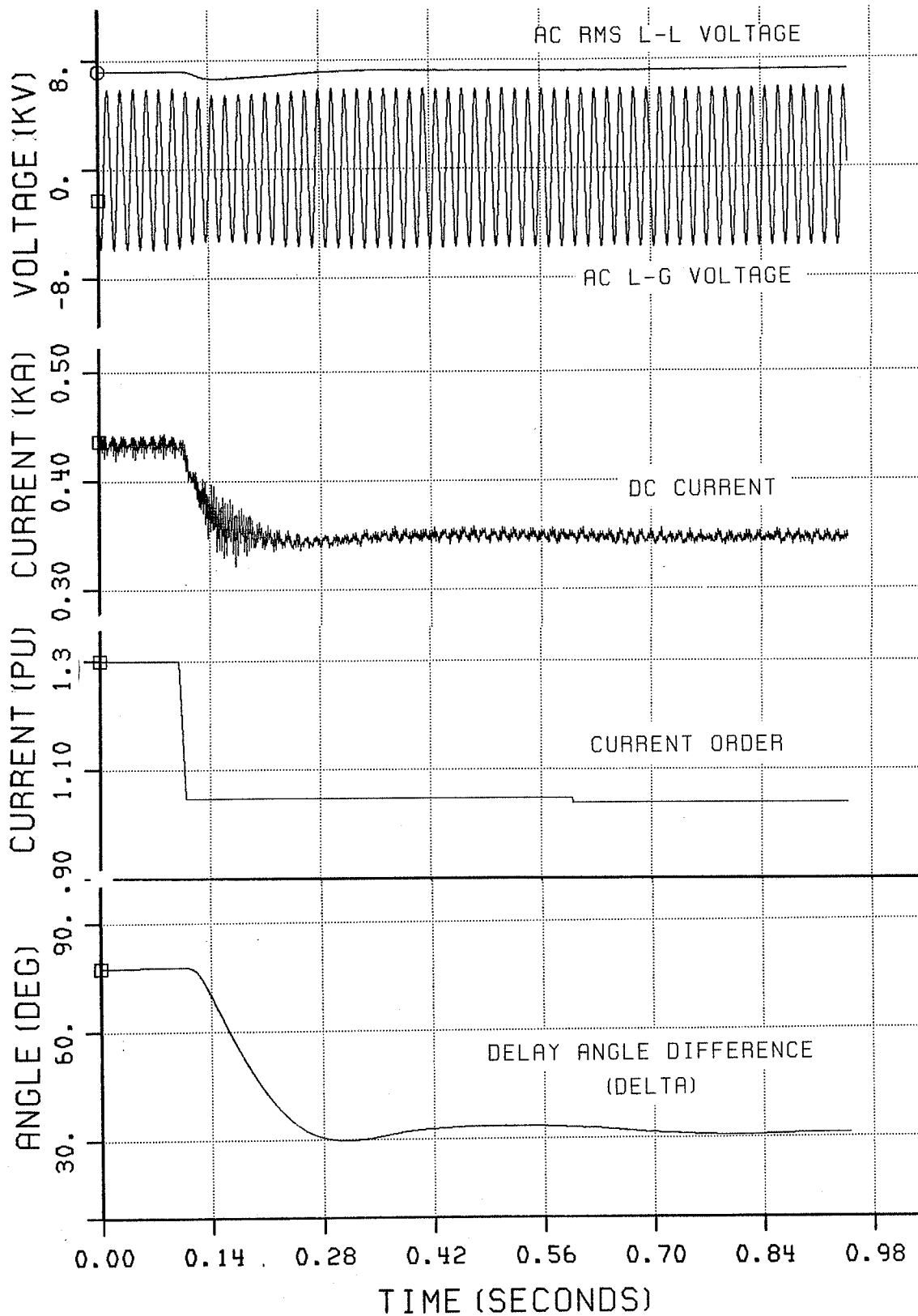


Figure 4.12: Operation at a desired  $\Delta$

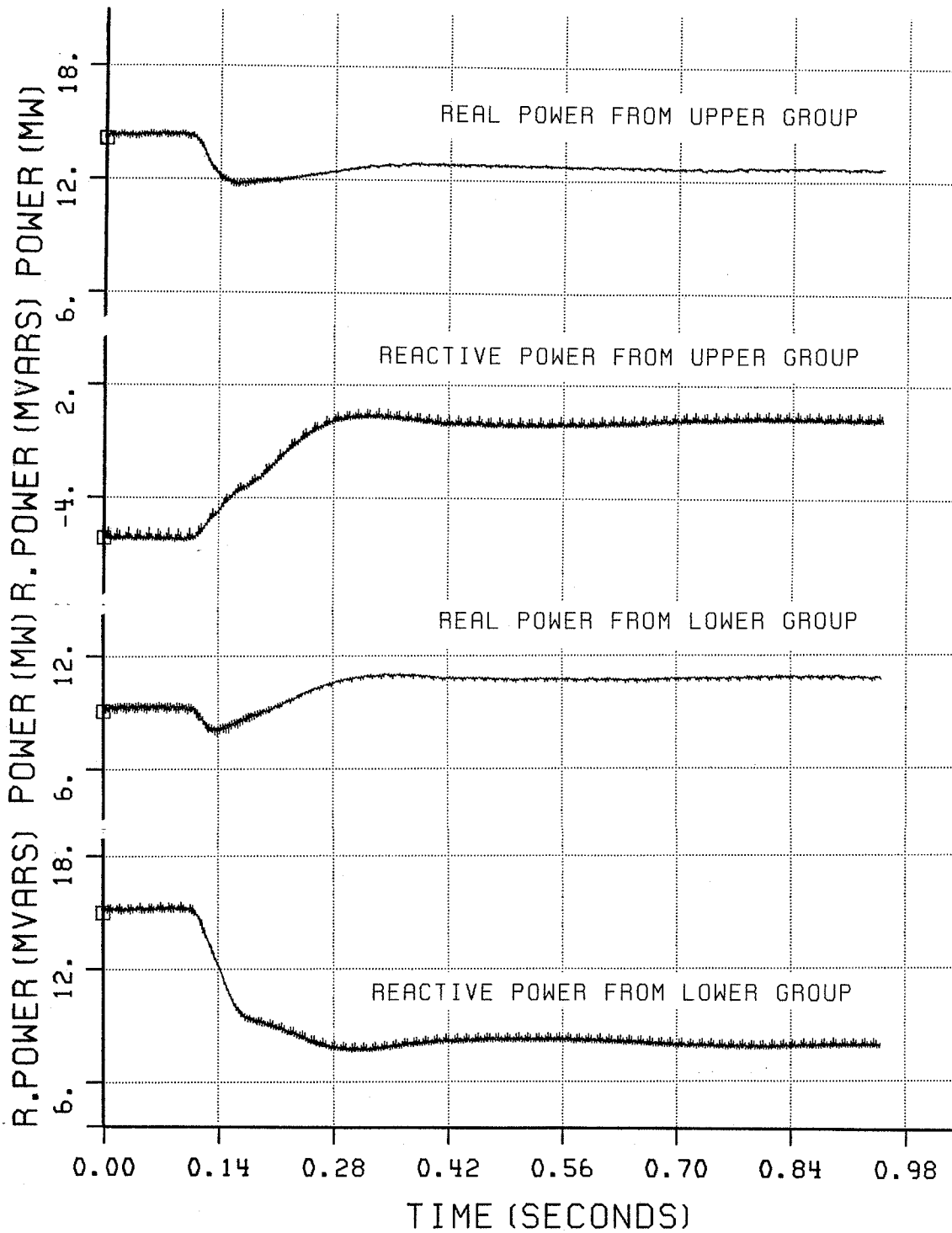


Figure 4.12: Operation at a desired  $\Delta$  (continued)

#### 4.5 A BRIEF ECONOMICAL ANALYSIS OF CHURCHILL SYSTEM

It is very difficult to achieve accurate cost comparisons between ac and dc transmission where a new technique is being proposed and the power level is only 5 % of the smallest installed HVDC system. Nevertheless several factors tend to indicate that the proposed scheme may be economically feasible.

At this power level ac line costs become significant. A voltage level of 138 kV is required for a single circuit uncompensated line of 310 km. Three conductors of at least 336.4 MCM must be used. The towers would be guyed and an expensive river crossing over the Nelson River is required. This can be compared to a simpler guyed single wooden pole tower carrying two 400 MCM conductors at a voltage level of 75 kV for 260 km. The use of two conductors increases the reliability as one conductor may break or fault and transmission can continue on the other.

In Section 3.7, an approach for an economical assessment on "Bipole 1 System" was presented. The same assumptions and methodology stated there apply also for the following brief economical analysis for the Churchill System. The system data and basic assumptions are :

- $V_d = 75$  kV,
- $I_d = 333$  A,
- $P_d = 25$  MW,
- 2 Bridge per pole, twelve-pulse operation,

- Inverter connected to 7.2 kV three phase network,
- Severe environmental conditions,
- All equipment except converter valves, control, protection equipment and auxiliaries are located outside,
- Ground return mode.

A conventional dc alternative with the above ratings and specifications to supply the town of Churchill has been reviewed at Manitoba Hydro and a survey has been recently conducted by BBC Brown, Boveri & Cie AG {37}. According to this proposal, the estimated cost of the converter terminals at both ends is shown below :

- Equipment :

Henday	Converter Station	\$ 4,200,000
Churchill	Converter Station	\$ 4,230,000
	7.2 kV, 8 MVA synchronous condenser	\$ 460,000

- Installation :

\$ 1,590,000

The work not included with the above figures are : all equipment on the line side of 230 kV breaker in Henday and 7.2 kV breakers in Churchill, service transformer and switchgear, compressed air system, dc line, ground electrode line, sea electrode at Churchill, telecommunication equipment, supervisory control, station groundings, spare transformers or any other spare equipment, test equipment, cabling.

The breakdown of the above described costs has been obtained from Mr. K.W. Kanngiesser of Brown Boveri by personal correspondence. This cost breakdown along with an estimated breakdown for the forced commutated alternative are presented in Table 4.3 .

The relative costs of the equipment affected by forced commutation for this project will be discussed next.

#### 4.5.1 Converter Transformers

Although two separate transformers at the inverter end are shown on the single line diagram in Fig.4.4, a single transformer unit with three windings on it could be utilized in order to reduce the expenses. Similar savings, as explained in "Bipole 1 System" cost analysis, are expected on the converter transformer MVA rating and secondary side insulation level. But their effects on the cost analysis would be only marginal on such a small project.

#### 4.5.2 Valves

The valve expenses for a naturally commutated inverter are given as 50 % of the total cost. The percentage appears quite high compared to that listed in Table 3.1 . This might be due to auxiliary equipment involved in valve cooling etc. Usually an accepted rule of thumb is that one third of the cost of the terminal is for the converter valves and about one quarter is for the transformer {23}. For a forced com-

TABLE 4.3

Estimated cost comparison for the Churchill System

<u>Equipment</u> <sup>(1)</sup>	<u>BBC</u>	<u>HMT</u> <u>F.C.</u>
Main Valves	0.500	1.150
Commutation Capacitors	-	0.110
Transformer	0.130	0.130
Smoothing reactor	0.050	0.050
Ac Filters	0.040	0.040
Synchronous condensers	0.326	-
Ac Switchyard	0.050	0.050
Dc Switchyard	0.050	0.050
Control & protection	0.140	0.140
Auxiliary equipment	<u>0.040</u>	<u>0.040</u>
Total	1.326	1.760
Ratings considered	+75 kV 333 A 25 MW	+75 kV 333 A 25 MW
Year considered	1983	1983
\$/kW per terminal	140.7	

(1) no installation cost included.

mutated alternative, the fixed factor of 2.3 would again be used for the valve expenses compared to natural commutation.

#### 4.5.3 Commutating Capacitors

The MVA rating of each capacitor used in the Churchill System is 6.1 MVA for the reliable and successful operation described before. Hence the total MVA rating of six capacitors would be 36.6 MVA. Using the \$/kvar figure supplied by Manitoba Hydro for the equipment only, the total capacitor expenses will be 13 % more on the total inverter station costs.

#### 4.5.4 Synchronous Condensers

Only one synchronous condenser is recommended in Ref.37 for the Churchill System. Presuming all the existing diesel generators will be taken out of service when the load is connected to the central system, the Churchill ac system consists only of passive components. The recommended synchronous condenser may be sufficient to run the system at a lower dc power to be transmitted, i.e. to supply the existing load varying from 1.25 MW to 6 MW. To run the system at the proposed load of 25 MW, the S.C.R. at Churchill has to be increased to a value around 3.0 pu. Technical data for the proposed synchronous condenser has not been supplied by BBC. Assuming an  $x'_d$  of 20-30 % on its own base, at least 3 of those synchronous condensers are needed for the satis-

factory operation of the naturally commutated scheme. Then the total cost of synchronous condensers would be about 32.6 % of the station cost.

#### 4.5.5 Ac Filters

For the natural commutation alternative, the system is designed for twelve-pulse operation. For the forced commutated alternative, although there are two valve groups in series, the operation is still six-pulse. Hence, this results in extra expenses of 5th and 7th filtering on the ac side. But in the cost analysis, this marginal cost has been ignored.

#### 4.5.6 General

As can be concluded from Table 4.3, the proposed forced commutated inverter alternative costs about 33 % more than the natural commutation alternative referred to the inverter station only. Considering the total cost of the project including the dc line, the cost of the forced commutated inverter would be only 4.6 % more. A natural commutation system requires a fast communication link to the rectifier end in order to control the receiving end system voltage. Also, maintenance and reliability of the synchronous condensers should be considered with such a system.

It is hazardous to attempt to extrapolate the cost of HVDC systems over several orders of power to the size of the

proposed system. Probably the cost of a similarly sized variable frequency synchronous motor drive would give a better cost estimate. It is reported by Electric Research Power Institute (EPRI) that pulse width modulated (PWM) inverters used to convert the dc power produced by fuel cells into ac power are under prototype construction {38}. For the converter rating of 10 MW and life of 20 years with nominal maintenance and repair, the cost is projected as US\$ 60-70/kW (1982 \$). (This selling price assumes production quantities of 150 units a year.) It is expected that the price might drop to about \$50/kW by the end of the decade, if the advances in electronics continue.

A 13.5 kV, 3.2 MW pilot power system with a forced commutated inverter, called "a voltage converter" by its authors, is already under construction in Soviet Union {39}.

#### 4.6 CONCLUSIONS

Results of the simulation studies have indicated that a forced commutated inverter can successfully supply a remote load without the need of rotating machines or reactive power support.

The scheme proposed can invert into such a load from no load to full load while maintaining the voltage and frequency within acceptable limits even for major load variations. The system easily survives ac side faults at the inverter and can quickly recover from dc line faults. Start-up and

operation of the system is simple and reliable, without a fast communication link between the terminals of the transmission system.

The results of simulation studies have indicated that the induction motor operating at the receiving end ac system can easily be started up and can successfully work during and even after the clearance of a dc line fault.

For this particular system, that is the supply of Churchill, Manitoba, the dc transmission alternative with forced commutation appears to be feasible from an economical standpoint as well as from a technical standpoint. Reliability and maintenance considerations also favour the forced commutation scheme.

## Chapter V

### A FORCED COMMUTATED INVERTER AS A TAP ON A DC LINE

#### 5.1 INTRODUCTION

A forced commutated inverter used for tapping energy to a remote load from a dc line running through a rural area is presented and a study conducted on Manitoba Hydro's electromagnetic transients program is described.

It is shown that a passive load requiring real and reactive power can easily be supplied. The tap itself is capable of responding quickly to changes of load without a communication link to the main converter terminals. The tap is able to recover easily from all anticipated faults and disturbances taking place in its own system as well as at the main converter terminals.

This chapter discusses the basic operating mode of the tap, the line and converter models and the ac system load model at the tap. The simulation results will be concerned with the interactions between the main inverter and the forced commutated tap during start-up, ac and dc faults and commutation failures taking place in both systems.

## 5.2 A GENERAL VIEW OF TAPPING POWER

To date most of HVDC transmission lines commissioned have been designed and operated to transfer power between two points, sending end and receiving end, probably due to cost of multiterminal systems. For a point to point system, it is possible to clear a fault on the line or in the converters by means of delay angle action to block the dc current temporarily. The lack of an economically feasible dc circuit breaker is still a drawback to the tapping or networking of dc systems. For a multiterminal system dc line fault protection requires good control features to bring the fault current to zero for arc extinction or to a level where a dc circuit breaker would be effective.

However, it is possible to tap the dc line provided that the control strategies of the tap and the main converter stations are considered together. The methods of doing this can be classified in two groups :

- i) The parallel tapped inverter,
- ii) The series tapped inverter.

The possibilities and advantages of these methods have been discussed in literature {40-46} especially in relation with the multiterminal operation. For a small tap to a weak ac system, the parallel arrangement suffers a disadvantage in that the tap is very sensitive to its own ac system faults. The disturbances on its own ac system might result in commutation failures and recovery of the system might be

difficult and may even require temporary blocking of the whole system. It has been shown the major disadvantages of the operation of parallel connected dc stations are {45} :

- i) A dc side fault affects the entire system. Loss of a dc line might result in the loss of the whole power transmission capability within the system. (In order to compensate such a situation, redundant lines can be added to the system at a certain cost.)
- ii) A commutation failure at any inverter results in excessive current drawn from the other terminals.
- iii) To achieve power reversal at one terminal, a mechanical switching arrangement is required since the valves can conduct current in only one direction (unidirectional feature).
- iv) If a single converter bridge at any terminal is to be blocked due to some disturbance, then the entire system should be operated at a lower voltage unless that particular terminal is completely disconnected.

It might be concluded that parallel connected multiterminal systems will be limited to only unidirectional power flow schemes without reversing switches across the bridge. Further developments of dc circuit breakers and the parallel connection of bridges might significantly enhance the versatility and flexibility of parallel connected systems {47}.

Parallel multiterminal dc transmission has the advantage of minimizing losses by operating at maximum line volts. Series tapped schemes suffer the disadvantage of operating with high line losses because of circulating current operation at less than maximum line volts.

The temptation to use a parallel inverter tap to minimize losses must be evaluated against the cost to strengthen the ac system to provide satisfactory performance. The other option is to examine the series tap with its savings in ac support equipment, or if forced commutation is used, needing no ac system supporting equipment at all.

Converter bridges are usually connected in series in a conventional HVDC terminal station. Therefore even a point to point system consists of more than one valve group all connected in series. The same idea could be extended for a multiterminal system {42} . The dc current will be flowing in the same direction through the main rectifier and inverter as well as the tap (Fig.5.1). By means of adjusting the delay angle high speed power reversal at any station is possible with no mechanical switching operation. Hence, both rectifier and inverter operation of each terminal could be achieved. Valve groups, even stations, could be taken into or out of service without effecting the rest of the system and the entire system will be less sensitive to system faults.

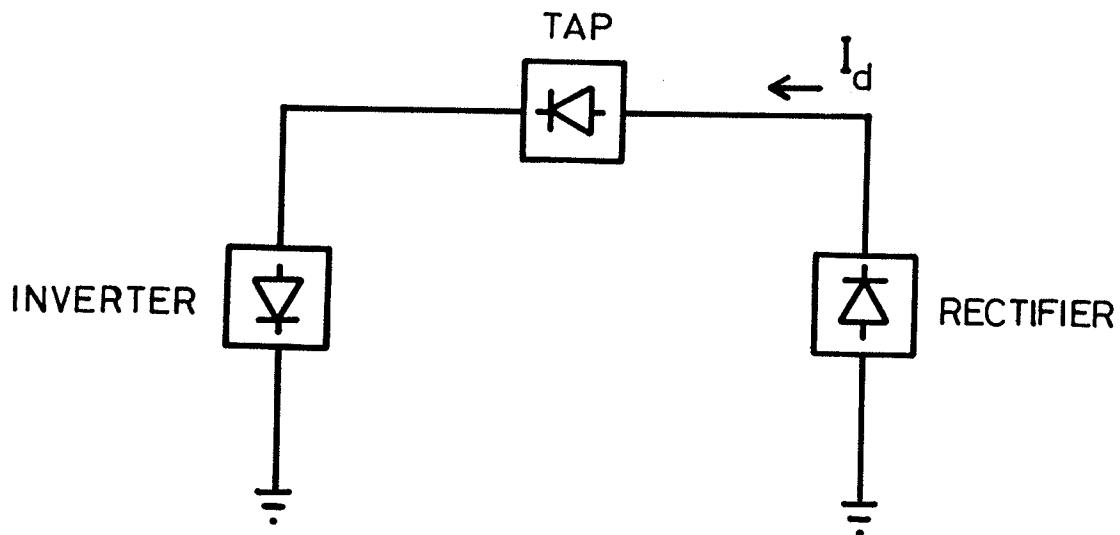


Figure 5.1: The series multiterminal dc system

A dc-ac machine set in series with the dc line has been proposed by Bowles, Nakra and Turner for such a tap {16} . The maintenance and repair of the rotating machinery must be considered when designing such a scheme.

### 5.3 A PARALLEL TAP

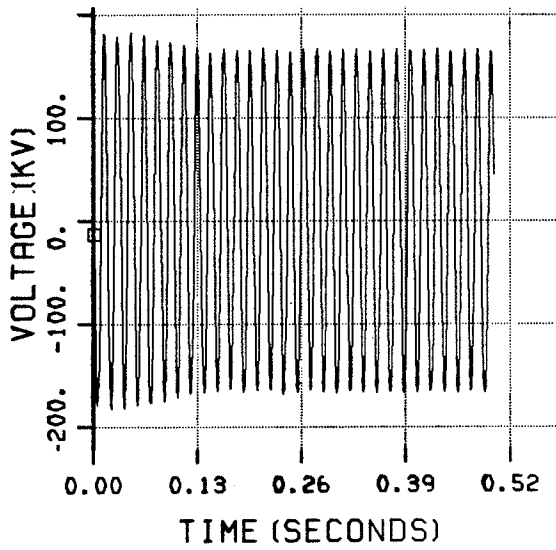
In the literature, it has been shown many times that the conventional point to point control strategies could be used successfully for parallel multiterminal dc systems {40,46,19,20}.

It is a well known fact that if the ac voltage at one of the converters in current control (CC) mode is reduced significantly, this converter will go to voltage control (VC) mode, hence lowering the voltage profile of the whole system. As a consequence, the converter which was primarily

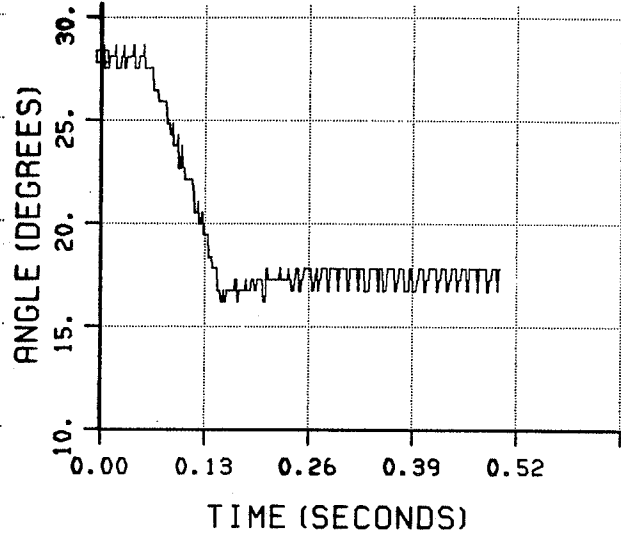
controlling the voltage has to switch to CC mode. If such a disturbance takes place at a rectifier, the mode shifts will proceed in a straight forward way. Such a case is reported in {46} and studied by the author. However if such a voltage dip occurs at a tap inverter station of relatively small rating, the inverter has to go to VC mode (constant extinction angle (C.E.A.) control mode for an inverter), otherwise it will be subject to large transient currents rejected from the larger inverter station(s).

Two different and new type of controls have been introduced by Nozari {48} and Sakurai et al {49} without the requirement of fast telecommunications. But, both of these studies have assumed infinitely strong ac systems.

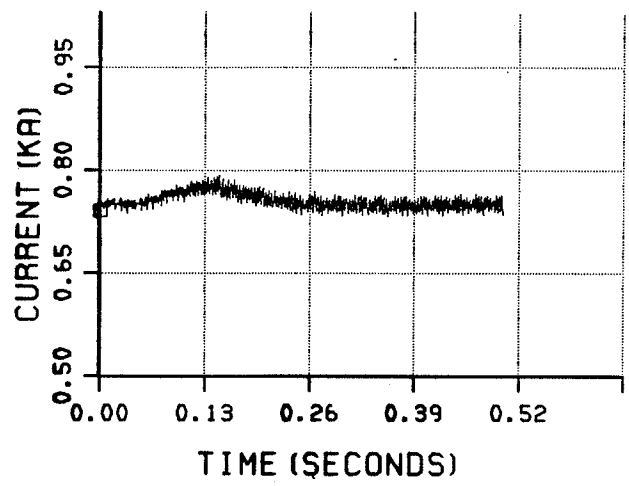
The above mentioned disturbance on the test system given in References 19 and 20 has been studied. (This is the same system studied by Institut de Recherche d'Hydro Quebec (IREQ) as part of an ongoing project sponsored by the Electric Power Research Institute (EPRI).) First of all, the system at the small parallel inverter tap location is designed with a strong ac system (short circuit ratio (S.C.R.) = 5.0 pu). In reference to Fig. 5.2, the ac voltage at the tap system is ramped down to 90 % of its nominal value within 100 ms starting at  $t=0.05$  s. Prior to the fault, the tap inverter was working in CC mode, hence with a larger gamma ( $28^\circ$ ). (One of the rectifiers at the sending end was assigned to control the voltage.) As seen from the figure,



a



b



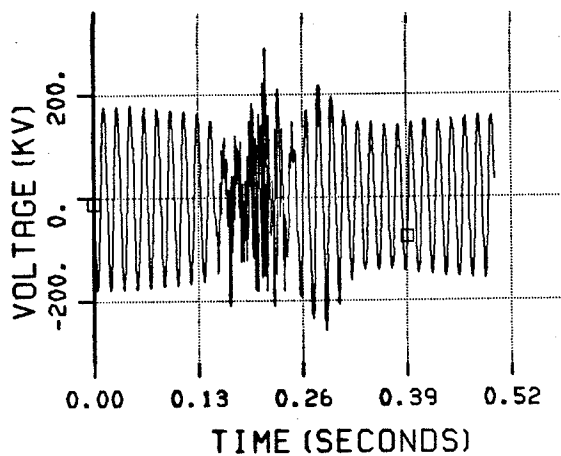
c

Figure 5.2: Fault at the tap ac system (S.C.R.=5.0 pu)  
 a - Voltage waveform at the tap inverter,  
 b - Gamma, c - Measured dc current.

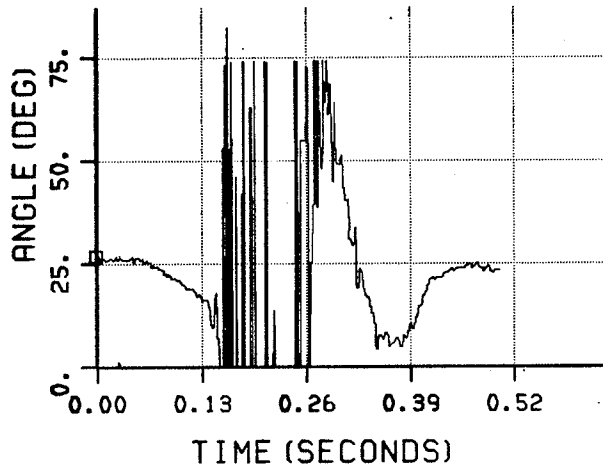
the mode shifts took place as expected almost instantaneously. The tap inverter has switched to VC mode operating with a margin angle of  $18^\circ$ , hence controlling the current injected into the ac system quickly. (No adjustment of current settings has been required at any of the converter stations.)

The same case has been repeated after adjusting the S.C.R. level of the tap ac system to be 3.0 pu (Fig.5.3). As seen from the figure, the tap system suffered from commutation failures. This may need control action such as blocking, forced retard, or reduced current order to enable recovery. It would normally be expected that such a slow rate of reduction of ac volts at the inverter would not create any cause for concern. But what is evident is that for small parallel inverter taps feeding into a relatively weak ac systems, even very minor perturbations in ac volts may lead to avalanche voltage collapse and drastic control measures such as blocking or forced retard and restart of the entire dc system.

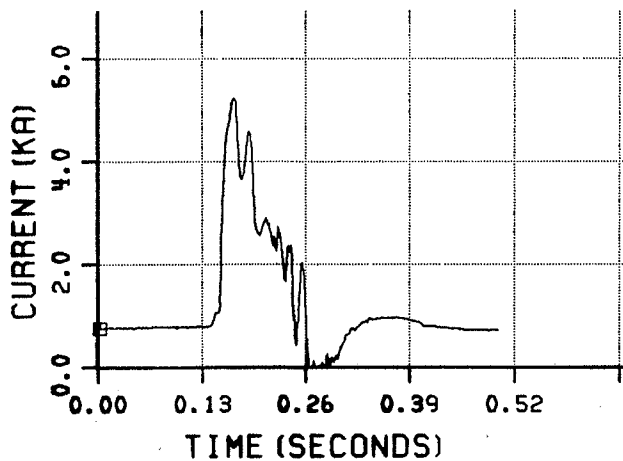
This then is a major disadvantage of the small parallel inverter tap. When weak ac systems are the case, the use of series taps must be seriously considered.



a



b



c

Figure 5.3: Fault at the tap ac system (S.C.R.=3.0 pu)  
 a - Voltage waveform at the tap inverter,  
 b - Gamma, c - Measured dc current.

#### 5.4 GENERAL DESCRIPTION OF THE PROPOSED SYSTEM

A simplified diagram of the proposed system is shown in Fig.5.4 . (The converter symbol used for main converters indicates that the station includes all the necessary equipment for an HVDC terminal.) The system consists of a conventional point to point scheme and a forced commutated tap inserted in series with the dc line. The proposed point to point system is supplying the remote load of Churchill. The series tap is located half way along the line and is, for example, to supply the railway system adjacent to the dc line with a power capability of 5 MW {32}.

The loads at Churchill and the railway system are supplied from a dedicated rectifier at Henday which uses the existing dc collector system including the filters and earth electrode. A monopolar dc line with a voltage rating of 75 kV runs between the main converters. The main rectifier and inverter stations are conventional naturally commutated converters with strong ac systems and are represented by only one six-pulse valve group each for simplicity of the studies. The tap is a series capacitor commutated inverter and employs two six-pulse bridges in series with the dc line; the operation being in six-pulse.

The ac system load at the tap is assumed to consist of only resistive and inductive elements. No rotating machinery is needed to support the reactive power to the converter (i.e. zero short circuit ratio system) . Conventional dc

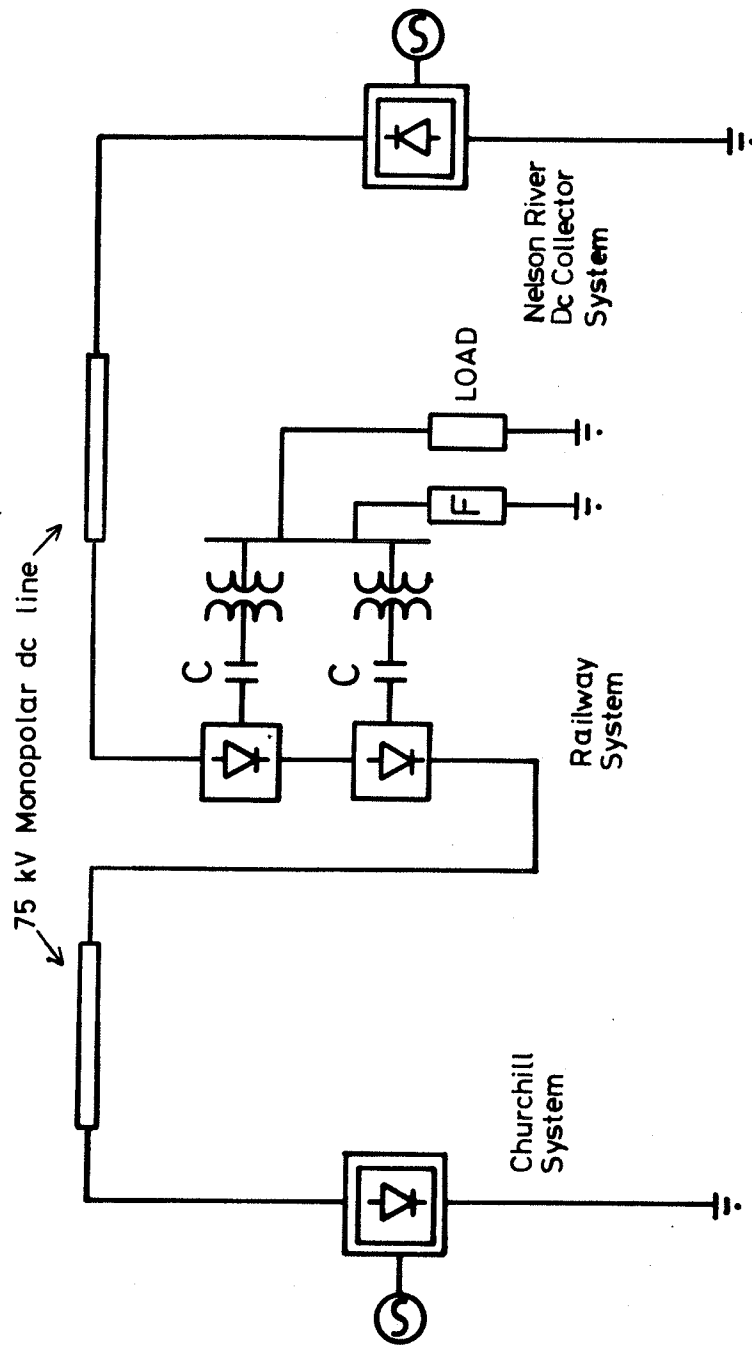


Figure 5.4: Proposed transmission system

controllers are employed at the main rectifier and inverter terminals. The rectifier is equipped with a constant current controller and the delay angle is adjusted to keep the current order at 1.2 pu at rated load. The inverter end is equipped with a constant extinction angle controller (gamma control) and minimum extinction angle is set at  $18^\circ$ . At the forced commutated tap, the firing control is derived from an independent clock producing exact ac frequency. A proportional and integral controller achieves good ac voltage control. The difference in firing angle order to the two valve groups ( $\Delta$ ) is utilized to control ac volts provided there is sufficient current flowing in the line.

The current order is defined depending upon the load requirements at the main inverter only. The tap system would have no control on the current order. Since the commutation capacitors are basically charged by the line current, as the current becomes higher more commutating voltage will be developed. But at low line currents, the tap might suffer from lack of sufficient commutating voltage. For this reason, the capacitors should be selected to develop adequate commutation voltage even at the minimum current level (usually around 0.3 pu).

The tap system might operate at any delay angle  $\Delta$  between  $0^\circ$  and  $180^\circ$  depending upon the load requirements of its own system and the current flowing through the line. If the delay angle  $\Delta$  is maintained at around  $30^\circ$ , the ac harmonics

will be less in the tap ac system. For this purpose, the converter transformers should be designed with a large range of tap changers, as dc current  $I_d$  is not under the control of the tapped inverter.

## 5.5 SIMULATION OF THE SYSTEM AND RESULTS

Again the performance of the system during the transient and steady state operation is observed. The recovery from various kind of faults at the receiving ends of the dc link are also important as far as the operation and reliability of the system is concerned. The results related to start-up, ac and dc side faults, commutation failures at the receiving end system and the effects of blocking and deblocking the main inverter on the tap system are presented.

### 5.5.1 Start-up of the System

The start-up of the system is very simple and fast, and takes place with the load on. At the beginning, the main converters are blocked and by-passed as in conventional point to point systems. The valve groups at the tap system are deblocked and operated at a delay angle of  $\Delta = 180^\circ$  before the main rectifier and inverter valve groups are deblocked. This effectively by-passes the tap on the dc side. When the rectifier is deblocked since the tap and main inverters are already by-passed, the dc current will rapidly rise to the value set by the pole controller at the rectifi-

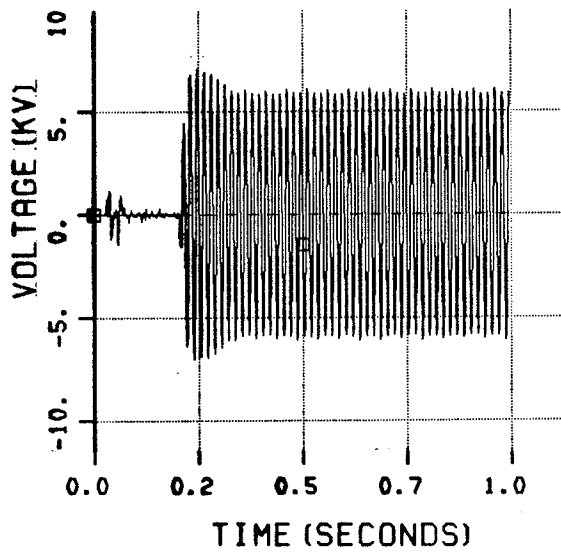
er. During this period, the dc current is circulating through the inverter by-pass switch and the tap from one bridge to the other, fully charging the commutating capacitors, but injecting no current into the ac system load.

Once the line is energized (at  $t=0.05$  s with reference to Fig.5.5), the inverter is de-blocked and the system works as in normal point to point system. The normal power transfer takes place between the main converter terminals. At  $t=0.2$  s the delay angle  $\Delta$  may be moved in a number of steps to its operating value set by the ac bus voltage controller (Fig.5.5-c). As the delay angle becomes smaller more current is injected into the tap, and hence the load voltage and power transfer increases to the rated value. The system is now in steady state and operates as described earlier.

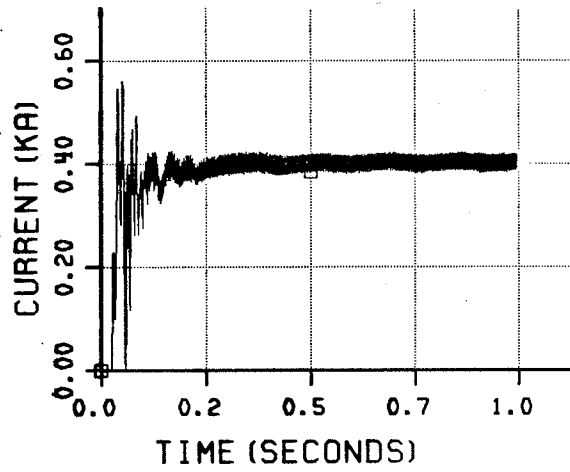
The start-up of the entire system takes about 0.4 s. By that time, the tap end ac voltage stabilizes to its set value. For transient voltage control,  $\Delta$  can be changed quickly by about  $20^\circ$  per commutation, without causing commutation failure. The tapped dc line with only one receiving station presents no problems during this start-up procedure.

### 5.5.2 Ac System Faults at the Main Inverter

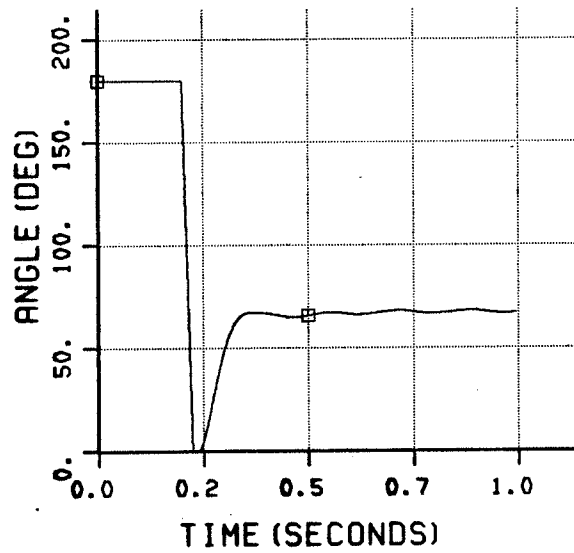
Near faults which might reduce the voltage drastically on the commutating busbar of the main inverter ac system are studied to observe their effects on the tap system. Usually these kind of faults result in commutation failures at the



a



b



c

Figure 5.5: Various waveforms during the start-up  
 a - Voltage waveform at the commutating busbar,  
 b - Measured dc current,  
 c - Delay angle difference,  $\Delta$

converter. The reduction of ac voltage due to a fault will reduce the dc voltage across the main inverter. This will cause the dc current to rise temporarily. The tap system should be able to respond to such changes. Figures 5.6 and 5.7 show the system response to three-phase-to-ground and single-phase-to-ground 3 cycle solid ac system faults at the main inverter system, respectively. The peak overvoltage at the tap ac system as a result of such faults is about 1.22 pu. No commutation failure or other disturbance occurred at the tap.

#### 5.5.3 Ac System Faults at the Tap

Figures 5.8 and 5.9 show the effect of three-phase-to-ground and single-phase-to-ground 3 cycle solid ac faults taking place at the tap system. These faults are not expected to cause a disturbance at the main inverter terminal because of the low power level of the tap. The tap system itself recovers in about 150 ms following the ac system faults. Overvoltages during the recovery of the system are within reasonable limits.

#### 5.5.4 Dc Line Fault

A dc line fault is a very severe fault for a forced commutated tap which is supplying a dead ac system. Because dc current is the source which charges the commutating capacitors, thereby providing the commutation voltage.

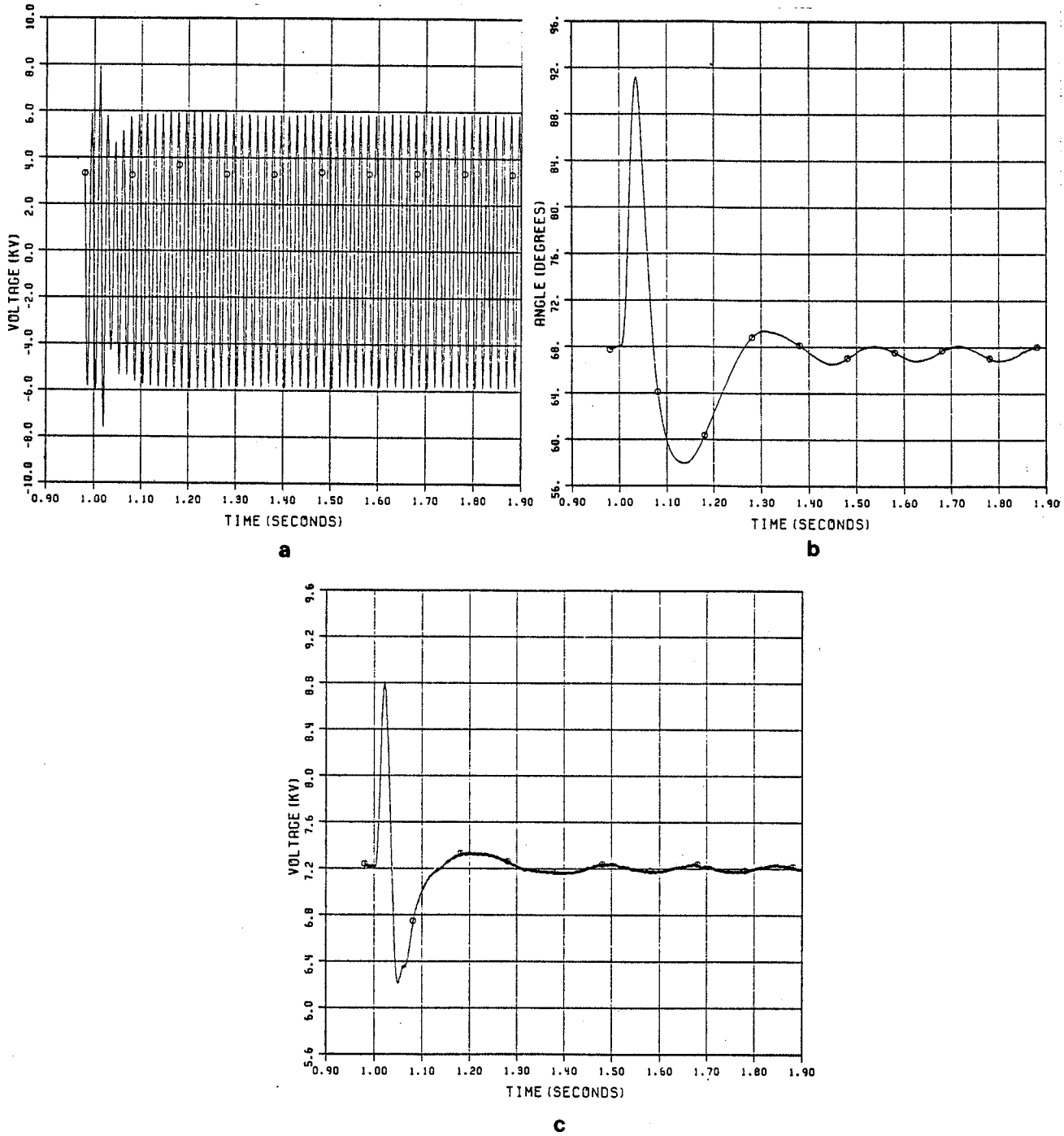
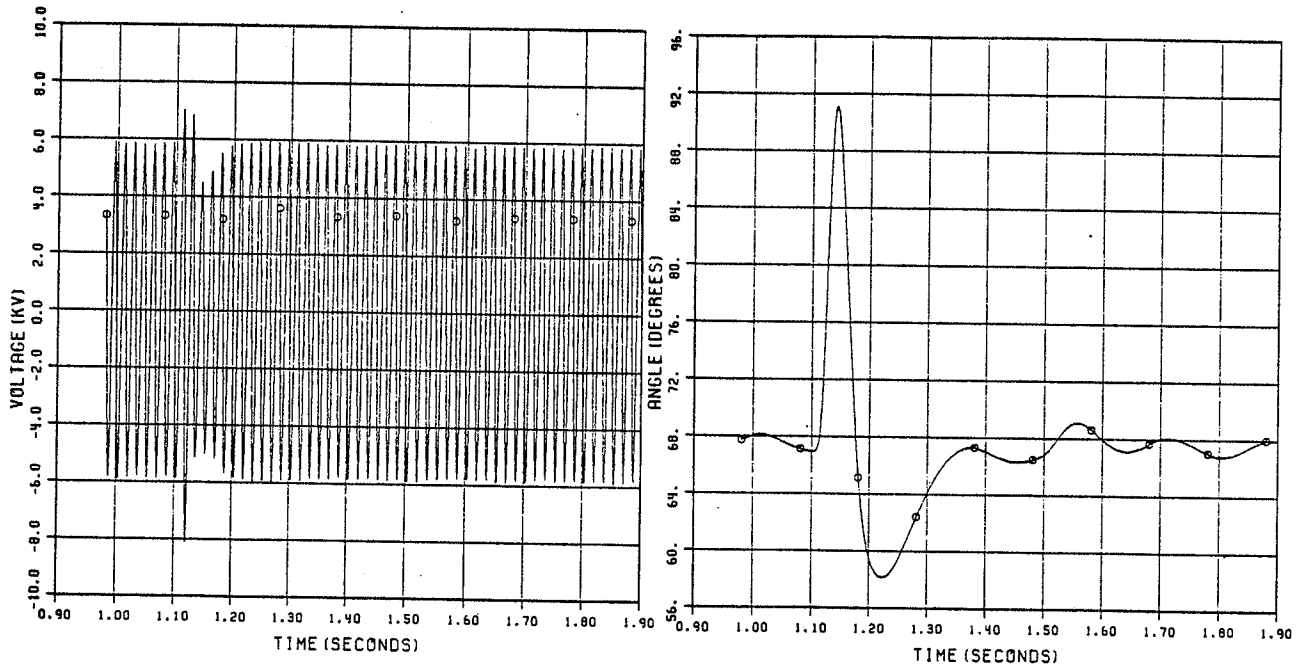
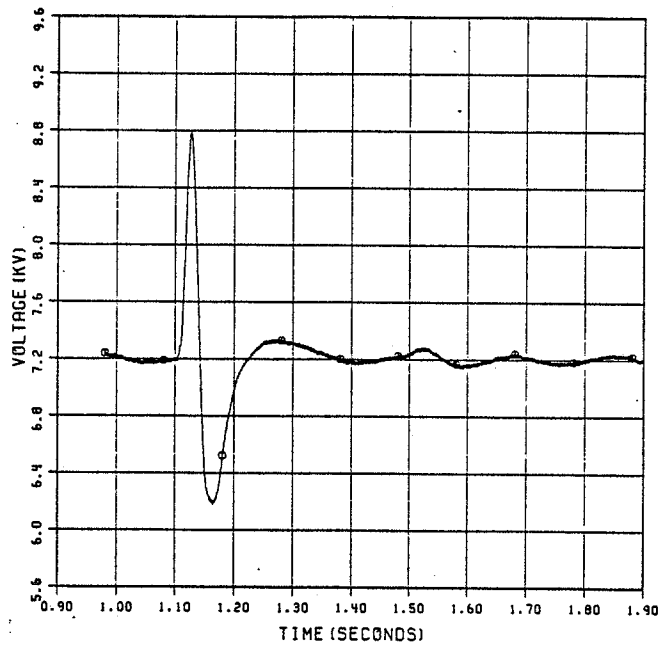


Figure 5.6: Various waveforms during a three phase ac fault at the main inverter  
 a - Voltage waveform bus at the tap,  
 b - Delay angle difference,  $\Delta$ ,  
 c - Measured ac rms voltage (1-1) at the tap



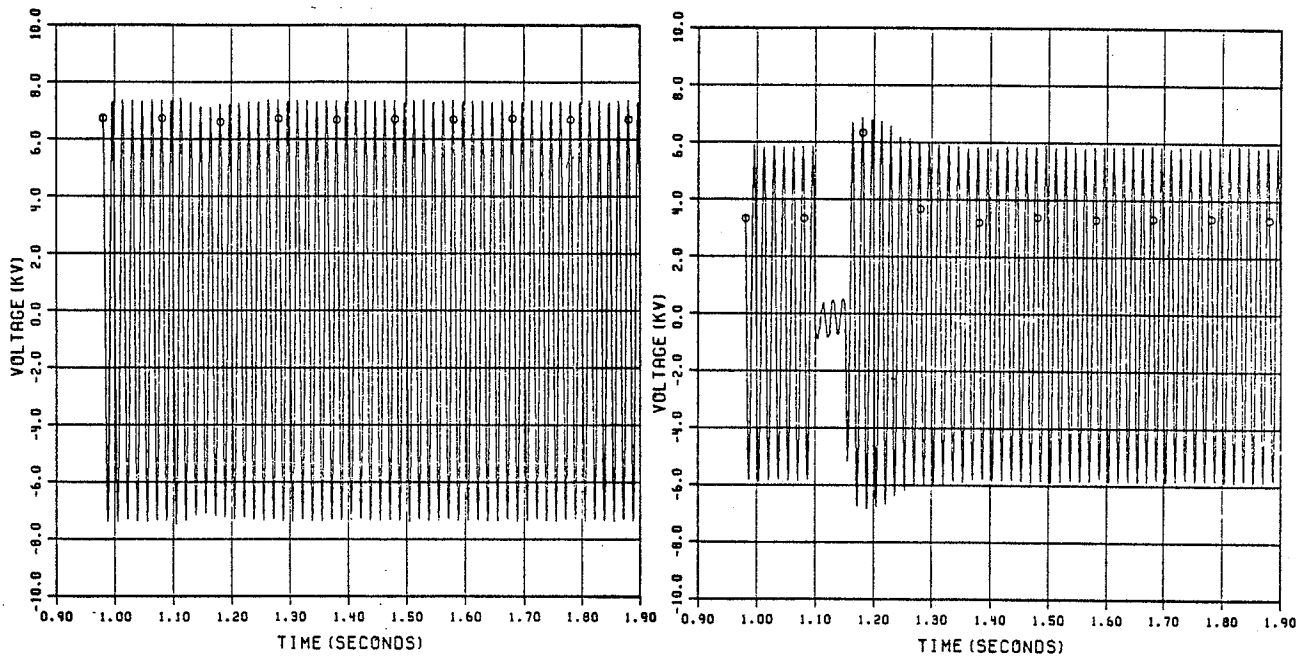
a

b



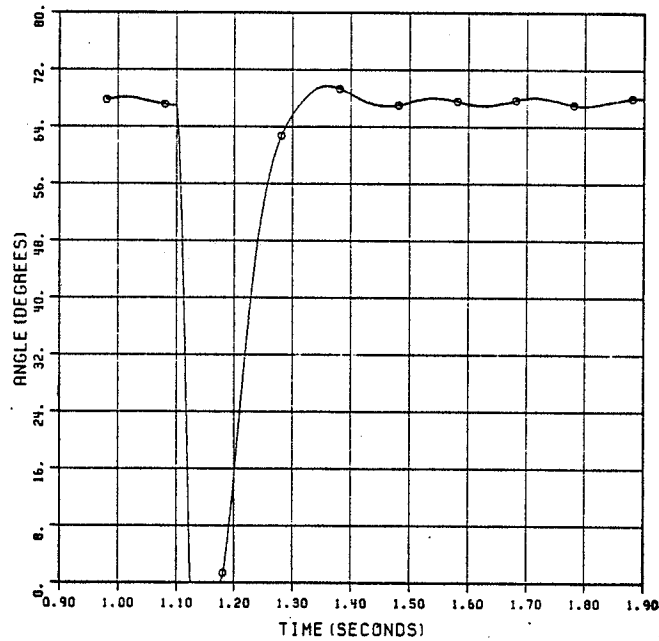
c

Figure 5.7: Various waveforms during a single phase ac fault at the main inverter  
 a - Voltage waveform at the tap,  
 b - Delay angle difference,  $\Delta$ ,  
 c - Measured ac rms voltage (l-l) at the tap



a

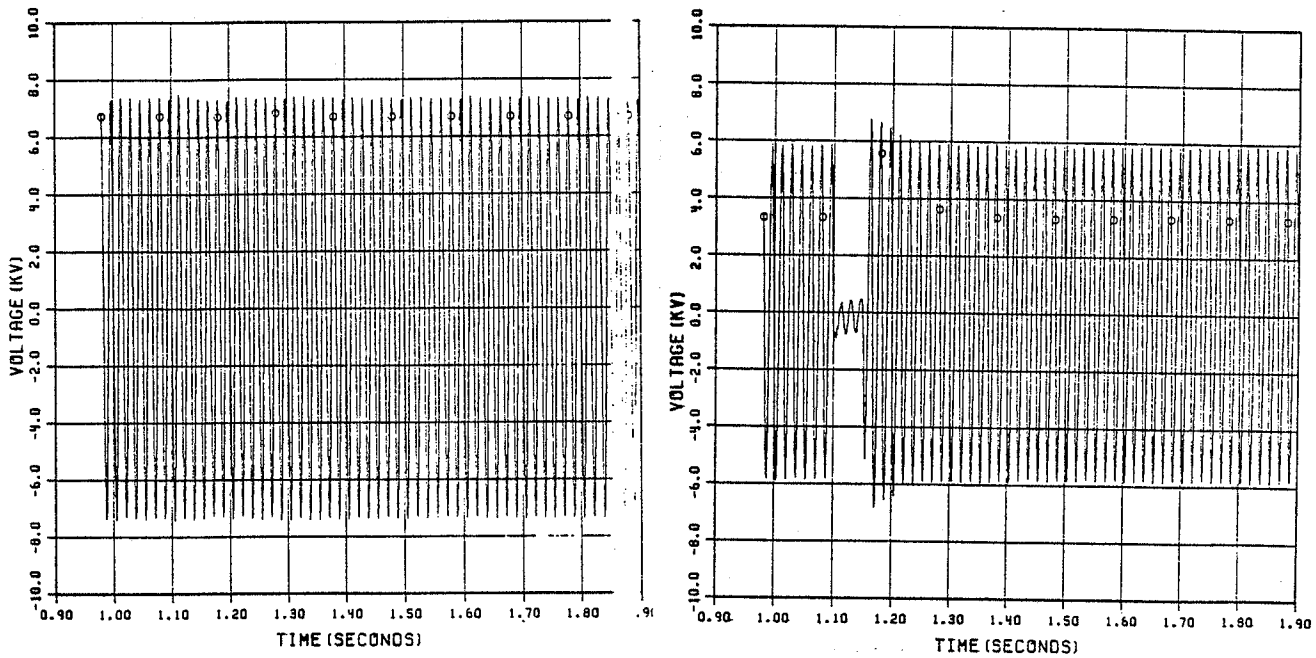
b



c

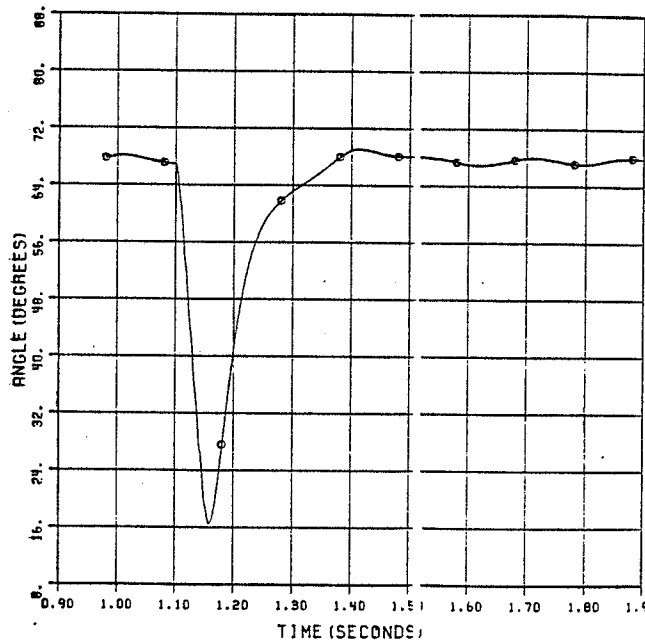
Figure 5.8: Various waveforms during a three phase ac fault at the tap

- a - Voltage waveform at the main inverter,
- b - Voltage waveform at the tap,
- c - Delay angle difference,  $\Delta$ ,



a

b



c

Figure 5.9: Various waveforms during a single phase ac fault at the tap  
 a - Voltage waveform at the main inverter,  
 b - Voltage waveform at the tap,  
 c - Delay angle difference,  $\Delta$ ,

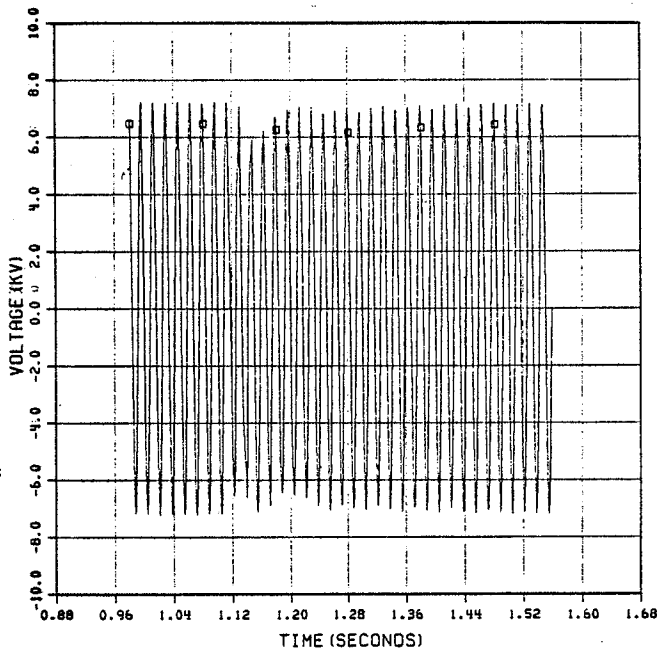
Once the fault is detected, the rectifier is forced-retarded to clear the fault. It is blocked and restarted after an adequate de-ionization time for the fault. The complete start-up procedure is to be applied for the multiterminal system. Since the situation is quite similar with the start-up study shown above no waveforms are presented here. The total duration of the disturbance at the receiving end ac systems is usually less than one second provided that the fault is not permanent.

#### 5.5.5 Commutation Failure at Main Inverter

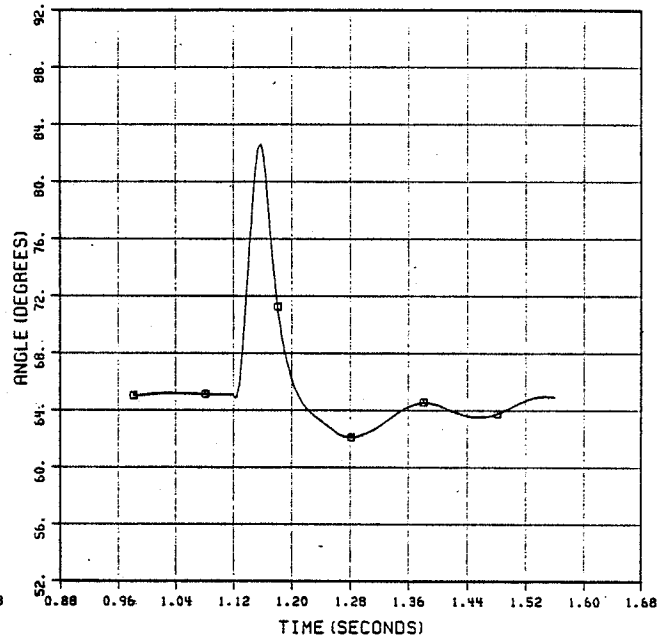
Some studies are performed to observe the effects of a commutation failure at the main inverter on the tap system. Figure 5.10 shows some waveforms during a 2 cycle commutation failure at the main inverter.

#### 5.5.6 Blocking and De-blocking the Main Inverter

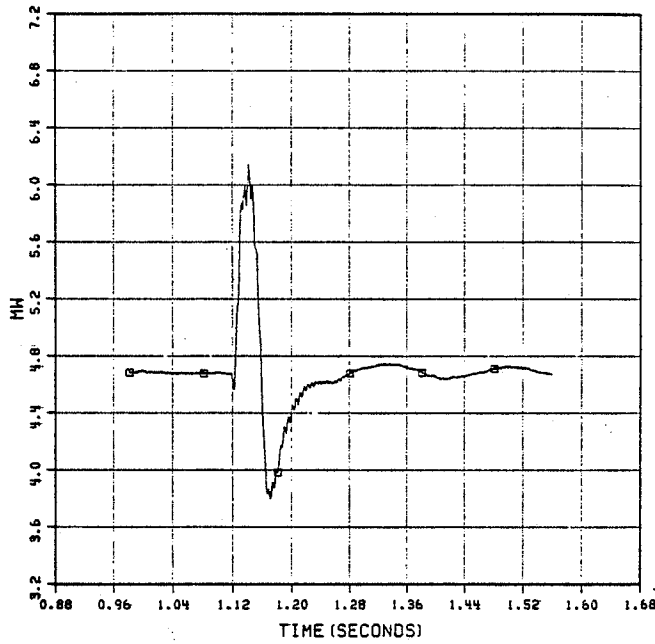
It might be necessary to block and by-pass the main inverter either temporarily or even permanently due to a fault. In such a situation, the tap system should still be able to receive the desired power. In a conventional point to point system, when the inverter is blocked, the current order is usually reduced to a fault level in order to reduce the reactive power requirements at the rectifier. But in the above described system, unless the capacitors are selected accordingly, reducing the current order to a fault



a



b



c

Figure 5.10: Various waveforms during a 2 cycle comm. failure at the main inverter  
 a - Voltage waveform at the tap,  
 b - Delay angle difference,  $\Delta$ ,  
 c - Real power into the tap.

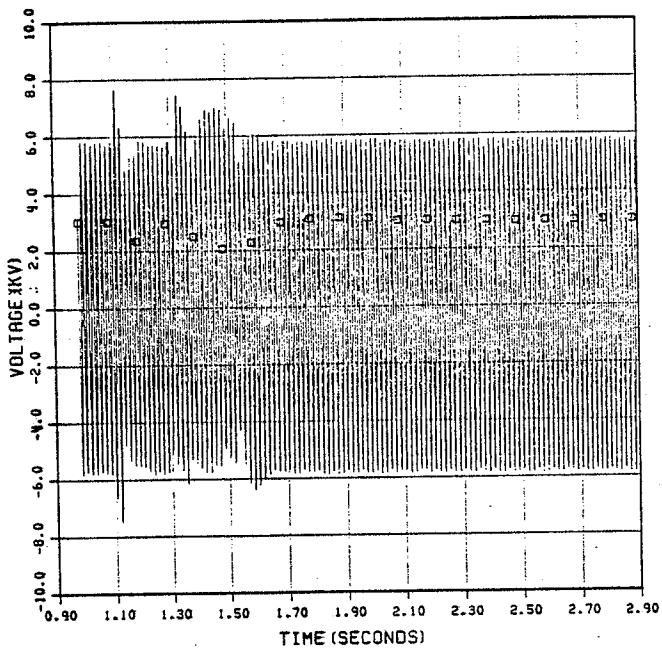
level (say 0.3 pu) will result in the commutation capacitors not acquiring sufficient voltage to provide the commutations. For the forced commutated tap the minimum dc current level is about 0.5 pu. Reduction of this minimum level results in increased valve stresses and therefore a compromise between valve stresses and minimum line losses must be made for any particular system.

The system was operating in steady state when the main inverter is blocked at  $t=1.1$  s with reference to Fig.5.11 . The tap system settles in less than 200 ms. At  $t=1.3$  s, the main inverter is de-blocked. This time tap system settles in about 0.4 s. Again the voltage swings on the tapped system are within reasonable limits.

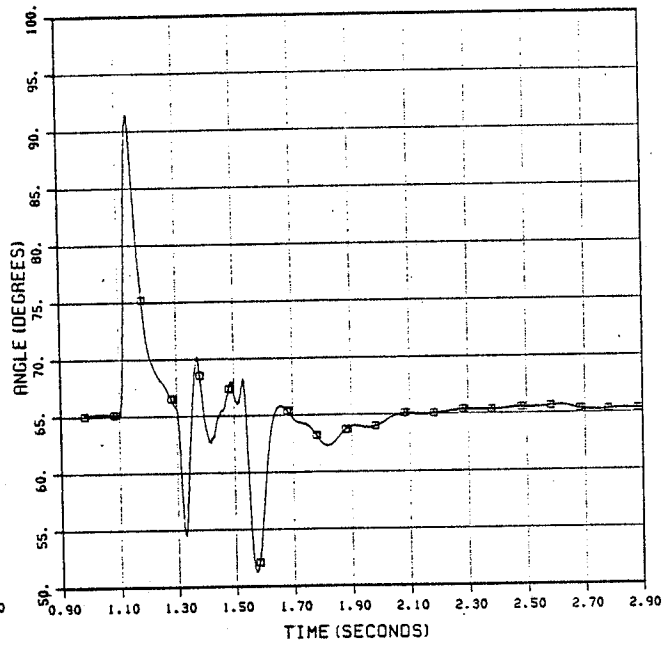
## 5.6 CONCLUSIONS

The results of the studies have shown that the concept of the series tap using a forced commutated inverter is technically feasible. Such a system could be operated successfully under transient and steady state conditions without the need of rotating machines or other means of reactive power support. Start up and operation of the system are simple and reliable even without a communication link to the remote tap system.

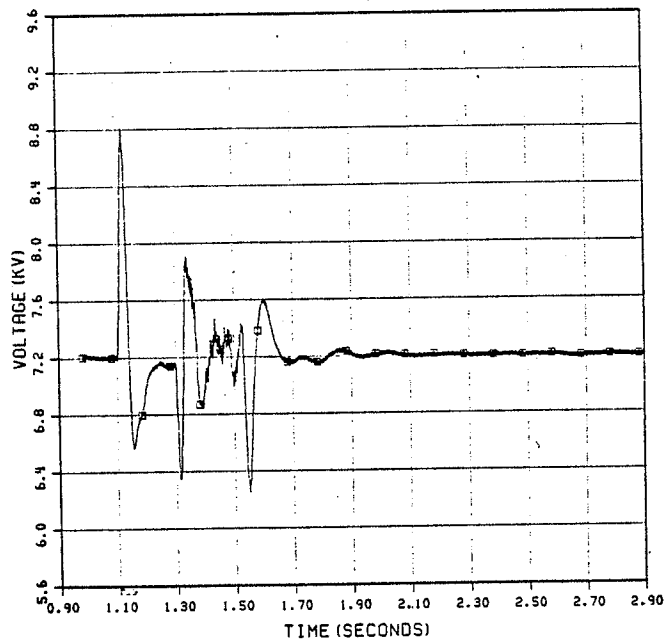
However it should be also mentioned that one drawback of series systems in general is that the system needs to be run at a high current level resulting in higher line losses and



a



b



c

Figure 5.11: Various waveforms during blocking/de-blocking of the main inverter  
 a - Voltage waveform at the tap,  
 b - Delay angle difference,  $\Delta$ ,  
 c - Measured ac rms voltage (1-1) at the tap

increased var requirements at the inverter terminals, even if one of the inverters is supplying a partial load. Therefore the series configuration can be restricted to short distance connections such as a ring system around an urban area for system reinforcement. If the inverters are forced commutated, although the current flowing through the line is high, the reactive power required by the inverters will be supplied by the inverters. Hence the forced commutation could be successfully utilized to improve the implementation of series schemes.

It was shown that the series inverter tap with forced commutation was not as sensitive to ac side disturbances as was the multiterminal system with a small parallel tap. This must be considered along with assessing the higher valve group costs of forced commutation and extra line losses of series tapped dc systems, particularly when comparison is made with costs of voltage support equipment and compensation for parallel inverter taps feeding into weak ac systems.

Chapter VI  
CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The main aim of this thesis has been to investigate the technical feasibility of forced commutation applicable to HVDC transmission. Several forced commutation schemes each having certain merits and demerits have been studied. For the operation of the forced commutated inverter in a point to point dc link and a series tap system, successful control techniques were developed. Also an approach for the economical assessment of the forced commutated terminal was completed.

The major conclusions are now stated in itemized form. The main conclusions in comparing the various schemes for forced commutation are :

- i) A forced commutated inverter has several advantages. Since the auxiliary devices (mostly pre-charged capacitors) provide the entire commutation voltage, the commutation can be almost independent of ac source voltage. Hence, the inclusion of auxiliary devices improves the ability to feed into weak, even dead ac systems.

- ii) The overlap angle is smaller than that for natural commutation; this introduces higher rates of change of current during the commutations.
- iii) Most of the forced commutation schemes require additional valves of full rating, called auxiliary valves, to apply the voltage across the commutating capacitor across the out-going valves. The two-step forced commutation circuit uses two additional valves. The one-step circuit uses a second fully rated bridge in addition to the normal bridge. The dc chopper scheme uses a minimum of two auxiliary valves. In the series capacitor commutated scheme, the number of valves is exactly the same as in the normal three phase bridge.
- iv) All schemes introduce higher voltage stresses across the valve in forward and reverse directions operating around the unity power factor.
- v) Harmonic distortions on the dc side are lowest with the one step forced commutation scheme.
- vi) Ac side harmonics with one-step, two-step and series capacitor schemes are at the same level as those of natural commutation. Both ac side and dc side harmonics are quite high with the dc chopper scheme.
- vii) Minimum current level is always a restriction with forced commutated schemes since it is the dc cur-

rent which charges the commutating capacitors. This becomes an important restriction with the two-step scheme since the capacitor is charged only during a small portion of one sixth of the cycle.

The studies of a two terminal dc transmission system feeding a weak ac network concluded that :

- i) Forced commutated inverters show significant advantages compared to natural commutated inverters especially in case of supplying weak ac networks.
- ii) Forced commutated inverters require no reactive power, therefore the use of synchronous condensers is eliminated.
- iii) Quick control of real and reactive power by means of delay angle can provide fast damping out of voltage fluctuations.
- iv) The forced commutated inverter is immune to the ac side faults at the inverter ac bus-bar. The system can quickly recover from the dc line faults provided that the fault is not permanent.
- v) The range of permitted firing angle cannot be increased beyond a certain angle for a given capacitor value and the dc current.
- vi) A forced commutated inverter operating near the unity power factor does not result in a dynamic overvoltage at the ac system when the valve groups are blocked. There is a possibility that this

might reduce the insulation level of the converter transformer and close ac system.

vii) The cost of a forced commutated inverter is slightly more compared to a naturally commutated inverter. The increased cost is due to higher valve stresses and commutation capacitors. But forced commutation brings the advantage of substitution of static components instead of synchronous condensers.

viii) Since the valve expenses constitute the large portion of the forced commutation costs, the lower escalation in the cost of dc equipment may make forced commutation more attractive in the future.

The conclusions in supplying a remote dead ac system by means of a forced commutated inverter are :

- i) It has been shown that employing two forced commutated six-pulse bridges in series, it is possible to supply a dead system without the need of rotating machines. The inverter can invert into such a load from no load to full load while maintaining the voltage and frequency within acceptable limits even for major load variations.
- ii) Start up and operation of the above mentioned system is simple and reliable without a fast communication link between the terminals of the transmission system.

- iii) The network voltage can be quickly regulated by means of  $\Delta$  when two six-pulse bridges in series are used to feed a dead system.
- iv) Line losses and harmonic stresses can be reduced by using a telephone communication link to the rectifier end.
- v) It has been demonstrated that the dynamic loads supplied from the forced commutated inverter can easily be started-up and can successfully work following the clearance of a dc line fault.
- vi) The proposed forced commutated alternative costs more than the natural commutation alternative referring to the inverter station only. However, reliability and maintenance considerations favour the forced commutation scheme.

The studies related with tapping power from a dc line concluded the following points :

- i) Forced commutation could be successfully utilized to improve the implementation of the series multi-terminal systems.
- ii) It was shown that the series inverter tap with forced commutation is not as sensitive to ac side disturbances as was the multiterminal system with a small parallel tap. This must be considered along with assessing the higher valve group costs of forced commutation and extra line losses of series

tapped dc systems, particularly when comparison is made with costs of voltage support equipment and compensation for parallel inverter taps feeding into weak ac systems.

## 6.2 RECOMMENDATIONS

In order to gain further expertise in the area of forced commutation, a prototype low power system could be built and tested with microprocessor-based controls and protection features. The studies presented in this thesis could be repeated on such a test system.

The control and protection of the forced commutation schemes are to be further improved and optimized.

Economical analysis presented in this thesis is by no means conclusive until exact costs can be established. The commutating capacitor, valve stresses, minimum current level, and line losses are the major items affecting the capital and operating costs of the system. Depending upon firm prices and system design criteria, the above mentioned items can be optimized.

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Appendix A  
PER UNIT SYSTEM

Using per unit systems in power system studies is quite advantageous since it is possible to express quantities such as voltage, current and impedance in a more meaningful way. In the selection of the per unit base values for a transformer, the constancy of the complex power on either side gives the basic equation to be satisfied. In case of a converter, it is the real power which is invariant since the converter itself does not consume any real power :

$$P_{dc} = P_{ac}$$

where

$P_{dc}$  = real power on dc side,

$P_{ac}$  = real power on ac side

Thus dc line current and ac line to line voltage are chosen as the base quantities. Because under normal operating conditions the dc current and ac line to line voltage are around 1.0 pu. The ratio between ac current to dc current can be derived as below.

$$P_{dc} = V_d I_d$$
$$P_{ac} = \sqrt{3} E_{LL} I_{10} \cos \phi$$

where

$V_d$  : Average dc voltage

$I_d$  : Dc current

$E_{LL}$  : Line-to-line rms volts on ac side

$I_{10}$ : Rms value of the fundamental component of ac  
current with no overlap

$\cos \phi$  : power factor

The average dc voltage  $V_d$  is defined as

$$P_d = V_d I_d \cos \alpha$$

where

$$V_0 = \frac{3\sqrt{2}}{\pi} E_{LL}$$

Then

$$\frac{3\sqrt{2}}{\pi} E_{LL} I_d \cos \alpha = \sqrt{3} E_{LL} I_{10} \cos \phi$$

Neglecting the effect of the overlap angle which is usually quite small, the displacement factor  $\cos \phi$  is approximately equal to  $\cos \alpha$ . Therefore

$$I_{10} = \frac{\sqrt{6}}{\pi} I_d$$

## Appendix B

### SYSTEM DATA USED FOR SIMULATION OF "BIPOLE 1 SYSTEM"

#### A) RECTIFIER END

##### Ac System

Ac busbar voltage  $V_{LL} = 138$  kV

$L_1 = 1.72$  mH

$L_2 = 1.85$  mH

$R = 0.933 \Omega$

##### Filters:

5th harmonic filter

$R = 3.0 \Omega$

$L = 0.1228$  H

$C = 2.29 \mu\text{F}$

7th harmonic filter

$R = 4.0 \Omega$

$L = 0.1228$  H

$C = 1.1685 \mu\text{F}$

11th harmonic filter

$R = 2.0 \Omega$

$L = 0.0304$  H

$C = 1.92 \mu\text{F}$

13th harmonic filter

$R = 2.0 \Omega$

$L = 0.0304$  H

$C = 1.374 \mu\text{F}$

high pass filter

$R = 42.0 \Omega$

$L = 0.0029$  H

$C = 5.5 \mu\text{F}$

##### Transformer data:

$V_{LL} = 138$  kV on primary side

$V_{LL} = 134$  kV on secondary (valve) side

MVA rating = 341 MVA per phase.

##### Dc System

Rated dc voltage  $V_{dr} = 463$  kV

Rated dc current  $I_{dc} = 1800$  A

Filters:

6th harmonic filter

$$R = 20 \Omega \qquad L = 0.388 \text{ H} \qquad C = 0.505 \mu\text{F}$$

12th harmonic filter

$$R = 25 \Omega \qquad L = 0.233 \text{ H} \qquad C = 0.2 \mu\text{F}$$

Smoothing reactors = 0.55 H each.

Surge capacitor = 0.5  $\mu\text{F}$

Valve damping circuit

$$R = 1460 \Omega \qquad C = 0.0867 \mu\text{F per bridge arm.}$$

B) INVERTER END

Ac System

Ac busbar voltage

$$L_1 = 0.12211 \text{ H} \qquad L_2 = 0.0856 \text{ H} \qquad R = 59.3 \Omega$$

Filters:

Although minimum cost filters 1 are designed for the inverter end, one set of Bipole 1 filters are used as a more pessimistic case.

5th harmonic filter

$$R = 4.0 \Omega \qquad L = 0.168 \text{ H} \qquad C = 1.67 \mu\text{F}$$

7th harmonic filter

$$R = 5.0 \Omega \qquad L = 0.168 \text{ H} \qquad C = 0.852 \mu\text{F}$$

11th harmonic filter

$$R = 2.0 \Omega \qquad L = 0.0444 \text{ H} \qquad C = 1.31 \mu\text{F}$$

13th harmonic filter

$$R = 2.5 \Omega \qquad L = 0.0444 \text{ H} \qquad C = 0.938 \mu\text{F}$$

high pass filter

$$R = 48.0 \Omega \qquad L = 0.00407 \text{ H} \qquad C = 4.04 \mu\text{F}$$

Transformer data:

$V_{LL} = 230 \text{ kV}$  on prim side

$V_{LL} = 327 \text{ kV}$  on secondary (valve) side

$S = 266.5 \text{ MVA}$  per phase.

Series Capacitor Data:

$C = 16.22 \mu\text{F}$  per phase.

### Dc System

Dc voltage  $V_{di} = 450$  kV nominal

Dc current  $I_d = 1800$  A

#### Filters:

6th harmonic filter

$R = 20.0 \Omega$

$L = 0.391$  H

$C = 0.5 \mu\text{F}$

12th harmonic filter

$R = 25.0 \Omega$

$L = 0.242$  H

$C = 0.202 \mu\text{F}$

Smoothing reactors = 0.55 H each.

Surge capacitor = 0.5  $\mu\text{F}$

#### Valve damping circuit

$R = 4380.0 \Omega$

$C = 0.0289 \mu\text{F}$  per bridge arm.

### C) DC LINE DATA

Line length = 556 miles

Line consists of 2 bundles. The total self-resistance on one path is nearly  $14.2 \Omega$ . The self inductance is about  $0.1624 \times 10^{-2}$  H, self capacitance of one path is  $0.01564 \mu\text{F}$ .

## Appendix C

### SYSTEM DATA USED FOR SIMULATION OF CHURCHILL SYSTEM

#### A) RECTIFIER END

##### Ac System

Ac busbar voltage  $V_{LL} = 230$  kV

$L_d'' = 0.01948$  H

##### Filters

5th harmonic filter

$R = 39.1 \Omega$                        $L = 0.675$  H                       $C = 0.417 \mu\text{F}$

high pass filter

$R = 134 \Omega$                        $L = 0.0049$  H                       $C = 10 \mu\text{F}$

##### Transformer data

$V_{LL} = 230$  kV on primary side

$V_{LL} = 70.3$  kV on secondary (valve) side.

MVA rating  $S = 31.6$  MVA total.

##### Dc System

Rated dc voltage  $V_{dr} = 82.2$  kV

Rated dc current  $I_{dc} = 0.333$  kA.

6th harmonic filter

$R = 20 \Omega$                        $L = 0.388$  H                       $C = 0.505 \mu\text{F}$

12th harmonic filter

$R = 25 \Omega$                        $L = 0.244$  H                       $C = 0.2 \mu\text{F}$

Smoothing reactors:  $0.085$  H each

Surge capacitor =  $0.5 \mu\text{F}$

Valve damping circuit

$R = 730 \Omega$                        $C = 0.1734 \mu\text{F}$  per bridge arm

B) INVERTER END

Ac System

Ac busbar voltage  $V_{LL} = 7.2$  kV

Filters

5th harmonic

$$R = 0.05 \Omega \quad L = 1.16 \text{ mH} \quad C = 242 \mu\text{F}$$

7th harmonic filter

$$R = 0.0595 \Omega \quad L = 0.961 \text{ mH} \quad C = 149.4 \mu\text{F}$$

11th harmonic filter

$$R = 0.07215 \Omega \quad L = 0.7565 \text{ mH} \quad C = 76.8 \mu\text{F}$$

13th harmonic filter

$$R = 0.0783 \Omega \quad L = 0.695 \text{ mH} \quad C = 59.91 \mu\text{F}$$

high pass filter

$$R = 5.05 \Omega \quad L = 0.606 \text{ mH} \quad C = 40.1 \mu\text{F}$$

Converter transformer data:

$V_{LL} = 7.2$  kV on primary side

$V_{LL} = 55.5$  kV of the secondary (valve) side

$S = 27.3$  MVA total

Series capacitor data:

$C = 17.8 \mu\text{F}$  in each phase

Diesel Generator data:

The diesel generator is modelled in a way that they are coupled to the system by a sub-transient reactance of 25% of its own base.

Assuming

$$S_{BASE} = 31.25 \text{ MVA}$$

Then the base impedance

$$Z_{BASE} = \frac{V_{BASE}^2}{S_{BASE}} = \frac{(4.15)^2}{10.4} = 1.656 \Omega$$

$$Z = Z_{BASE} \times X_d \text{ pu} = 1.656 \times 0.25 = 0.414 \Omega$$

$$X_d'' = j\omega L_d'' \quad L_d'' = \frac{0.414}{377} = 1.0981 \text{ mH}$$

The Load:

The load is supplied through a distributing transformer which has 10% impedance on its own base.

$$Z = Z_{BASE} \times Z_{pu}$$
$$= 1.656 \times 0.1 = 0.1656 \Omega$$

$$L_{tr} = \frac{0.1656}{2\pi 60} = 0.439 \text{ mH}$$

The load is modelled in different ways depending upon the purpose

- i) A series R and L branch (Fig. C.1-a).
- ii) A parallel R and L (Fig. C.1-b).
- iii) A parallel R and L with 5% motor load (Fig. C.1-c).

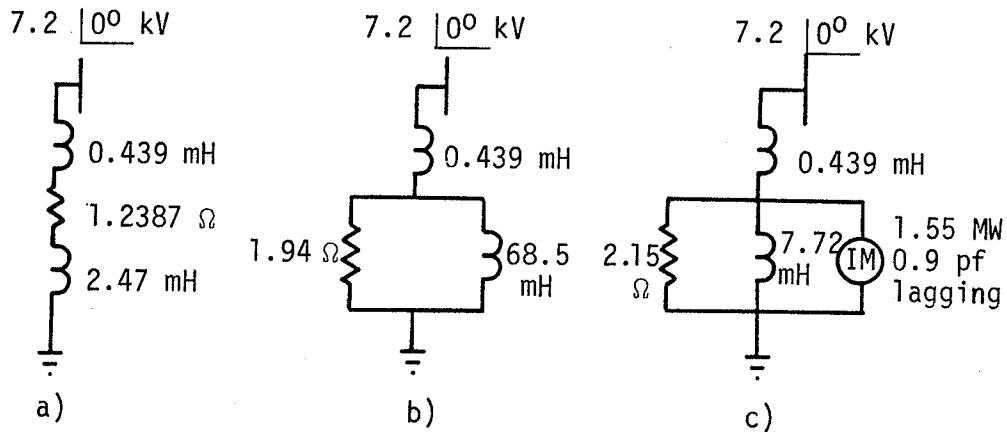


Figure C.1: Various Load Representations at Churchill

Dc System

Dc voltage  $V_{di} = 75 \text{ kV}$

Dc current  $I_d = 0.333 \text{ kA}$

6th harmonic filter

$R = 20 \Omega$

$L = 0.391 \text{ H}$

$C = 0.5 \mu\text{F}$

12th harmonic filter

$R = 25 \Omega$

$L = 0.242 \text{ H}$

$C = 0.202 \mu\text{F}$

Smoothing reactors = 0.085 H each

Surge capacitor: 0.5  $\mu\text{F}$

Valve damping circuit

$R = 345 \Omega$

$C = 0.3456 \mu\text{F}$  per bridge arm.

C) DC LINE DATA

666.6 MCM ACSR 75 kV Monopolar line

Dc resistance of line  $R_{dc} = 0.135 \text{ } \Omega/\text{mile}$

Modifications for System C

For System C, some of the dc and ac equipment is modified. The major modifications of the system data are as follows:

The active power rating for each bridge =  $\frac{25 \text{ MW}}{2} = 12.5 \text{ MW}$

Assuming unity power factor operation:

$$12.5 \text{ MW} = \frac{3\sqrt{2} E_{LL}}{\pi} I_d \cos \phi = \frac{3\sqrt{2} E_{LL}}{\pi} \times 0.333 \times 1.0$$

Then,

$E_{LL} = 27.77 \text{ kV}$  on the secondary side,

$E_{LL} = 7.2 \text{ kV}$  on the primary side (as in Systems A and B).

Transformer Data:

$E_{LL} = 7.2 \text{ kV}$  on prim side

$E_{LL} = 27.77 \text{ kV}$  on sec side

$$S = \frac{27.3 \text{ MVA}}{2} = 13.66 \text{ MVA total per each transformer}$$

$S = 4.55 \text{ MVA}$  per phase

Energizing current = 0.2% of rated primary current.

pu leakage impedance from side 1-2 = 0.1 pu.

Series Capacitor Data:

$X_C = 0.9 \text{ pu}$

$V_{BASE} = 27.77 \text{ kV}$

$I_{BASE} = 0.333 \text{ kA}$

$$Z_{BASE} = \frac{27.77 \text{ kV}}{0.333 \text{ kA}} = 83.31 \text{ } \Omega \quad (\text{base impedance of the hybrid system})$$

$$X_C = 0.9 \times 83.31 \text{ } \Omega = 74.98$$

$$C = \frac{1}{377 \times 74.98} = 35.4 \text{ } \mu\text{F}$$

Other dc and ac filters remained unchanged. Also snubber circuit parameters are updated accordingly.

Appendix D  
INDUCTION MOTOR DATA

Considering that Churchill load consists of also grain elevators, small induction motors in houses as well as the passive heating and lighting type of load, 5% of the total rated load is represented by induction motor load. The performance of start-up and steady-state operation is observed with such a combined load.

The load machine data is as follows:

$$V = 2.309 \text{ kV line to neutral.}$$

$$I = 0.111 \text{ kA per unit}$$

$$S = 0.6 \text{ MVA per unit}$$

$$\text{No. of units} = 2.22$$

$$X_a = 0.0908 \text{ pu}$$

$$X_{md} = 5.032 \text{ pu}$$

$$X_{kf} = 0.1451 \text{ pu}$$

$$X_{kd} = 0.0 \text{ pu}$$

$$X_f = 0.0539 \text{ pu}$$

$$X_{mq} = 5.032 \text{ pu}$$

$$X_{kqf} = 0.1451 \text{ pu}$$

$$X_{kq} = 0.0 \text{ pu}$$

$$X_{qf} = 0.0539 \text{ pu}$$

$$R_a = 0.01463 \text{ pu}$$

$$R_f = 0.0102 \text{ pu}$$

$$R_{qf} = 0.0102 \text{ pu}$$

$$R_{kd} = 0.04446 \text{ pu}$$

$$R_{kq} = 0.04446 \text{ pu}$$

$$H = 0.7 \text{ s}$$

$$\omega_0 = 377 \text{ rad/s}$$

$$\sigma = 1.0 \text{ (damping)}$$

Linear saturation curve characteristic is assumed.

The rated load of the machines

$$P_{LOAD} = 1.55 \text{ MW} \quad 0.9 \text{ pf lagging}$$

$$Q_{LOAD} = 0.75 \text{ Mvars}$$

The mechanical load on the machines is represented by a fan type of load i.e.

$$T_{mech} = k \times \omega_r^2$$

For a quick start-up, the inertia of the machine is kept smaller than its rated value and afterwards it is adjusted.