Stability Analysis of Multiterminal HVDC Links

Tapas Shome

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Electrical and Computer Engineering
University of Manitoba
Winnipeg, Manitoba

September 22, 1990

ISBN 0-315-71947-8

STABILITY ANALYSIS OF MULITERMINAL

HVDC LINKS

BY

TAPAS SHOME

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

MASTER OF SCIENCE

Acknowledgement

This research was carried out under the guidance of Dr. A. M. Gole, Associate Professor of Electrical Engineering, whom I would like to thank for his continued guidance and encouragement.

Also, I would like to express my sincere gratitude to Mr. Dennis Woodford, Executive Director of Manitoba HVDC Research Center, Mr. Dennis Brandt of Manitoba Hydro and Mr. Robert Hamlin of Manitoba Hydro for their advice and encouragement provided throughout the project. In addition, I would like to express my sincere gratitude to Professor M. Z. Tarnawecky of Electrical Engineering Department and Mr. Garry Mazur of Manitoba Hydro for encouraging me to undertake the theoretical analysis of stability, which is in essence the backbone of this thesis.

The author also wishes to express acknowledgment to Manitoba Hydro and NSERC for funding this research project. Finally, I would like to express my appreciation to my friends in Electrical Engineering Department and Mr. Erwin Dirks of Power System Simulation Laboratory in particular, for making life so much enjoyable.

Contents

List of Figures

Chapter 1

General

1.1 Introduction

A significant feature of the HVDC transmission is that direct control of HVDC links is provided through delaying or advancing the firing instants of the individual valves. This control action is much faster compared to the control actions necessary to regulate the active power flow in ac machines. Moreover, the concept of stability as applicable to ac and dc system is considerably different. The stability of the dc system is a major topic in itself and requires the understanding and manipulation of electronic rather than electric circuits.

An attempt at solution can be made with either digital simulation or frequency domain stability analysis. A staraight forward application of the latter such as small signal analysis is often not suitable because of unconventional modulation and denodulation process involved when the converter is connected to an weak AC system. The decribing function method which handels larg signal systems is perhaps more suitated and some development has been carried out in this thesis. Time domain simulation although quite inefficient is straight forward to use and has been used in this thesis to solve a stability problem associated with parallel dc system. In order to properly model a dc-ac system, proper modelling of the following parameters is necessary.

1. Phase Locked Loop synchronization time constant.
2. Unbalance, harmonics and distortion in the ac bus voltage.
3. AC and dc filter impedance and in particular harmonic impedance.
4. DC system configuration– whether multiterminal or not.
5. Converter transformer saturation
6. Unbalance in the converter-transformer leakage impedance.
7. Dynamics of the Pole Controller, Valve Group Controller and Current Balance and Current Difference Controller.

1.2 Statement of the Problem

The Nelson River HVDC system of Manitoba Hydro shown schematically below in Figure 1.1 has two bipolar dc circuits, which bring power from the generating stations on the Nelson River to the Southern load centers over roughly 900km of terrain. The first circuit Bipole 1 is rated at 463.5kV and 1800A and has the three 154kV mercury arc valves groups per pole. Bipole 2 is rated at 500kV, 1800 A and has two 12 pulse thyristor valve groups per pole. Control modifications have been implemented, and high speed switches provided to allow parallel operation of any one pole on a single transmission line, in the event of the unavailability of the transmission line. The initial paralleling was carried out at low voltage with one 154kV Bipole 1 six pulse valve group paralleled to one 250kV Bipole 2 twelve pulse valve group to prove control concepts and modifications. During paralleling operation, the 250kV valve group is operated at a lower voltage, so that both valve groups have the same voltage. These tests were carried out in the summer of 1982. High voltage paralleling with full 463.1 kV of Bipole 1 and 500kV pole of Bipole 2 were carried out in 1985 and 1986.

The block schematic of the paralleling controls is shown in Figure 1.2. The paralleling logic-block coordinates the closing of the high speed switches, and also assigns the correct current orders to the current (pole) controllers that are paralleled. The valve group control-block either passes on the pole controller's firing angle order, or selects another firing angle based on whether there is need for other forms of control such as: constant extinction angle control or current error control. Figure 1.3 shows typical inverter characteristics outlining the meaning of CEA, CC and current error (CE) control. By changing the tap changer ratio, the inverter characteristics can be made to intersect the rectifier characteristics in any one of these three modes.

Figure 1.4 and Figure 1.5 shows two inverters and two rectifiers operating in parallel. As the rectifiers uncontrolled characteristics are at a larger voltage than the inverter's characteristics, the rectifiers are in constant current control with Id1=Idref1, Id2=Idref2. The common voltage line (dotted) intersects one inverter in the CE characteristic and the other on its constant current characteristic. (By kirchoff's current law Id1+Id2=Id3+Id4). Note that further dropping of the ac voltage on inverter 4 will result in its going into CEA operation. Note that exactly one of the inverters, say inverter 4, is in a voltage control and absorbs the spill current Id1+Id2-Id3. During paralleling tests in 1985, it was observed that a mode of operation was possible with the rectifiers in stable, constant current operation, but with the inverters having a six hertz current oscillation. Figure 1.6-1.9 shows the field recordings of this phenomena. The oscillation only occurred with the inverter of bipole 2 in current error control and the inverter of bipole 1 in CEA control. If the tap-changer-ratio of Bipole 2 were increased, so that it went into constant operation, the oscillation would cease.

It was observed that the dc line current (sum of two rectifier currents) was constant without oscillations. Thus the rectifier did not seem to play a role in the phenomena. Also, the ac side bus voltage on the inverter appeared to be sinusoidal and essentially free of low frequency oscillations. Thus there appeared to be no relationship between this dc oscillation and the ac side system.

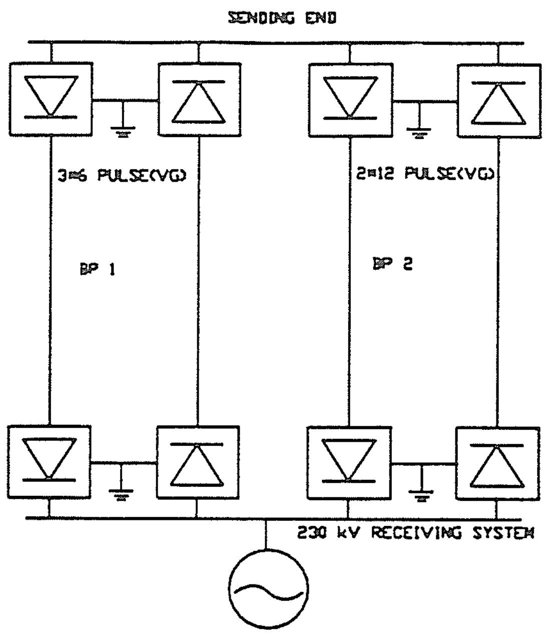


Figure 1.1: Nelson River transmission system

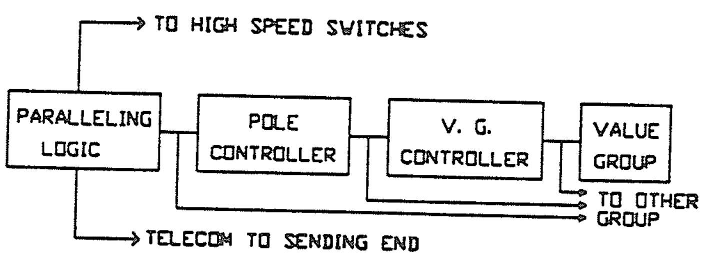


Figure 1.2: Schematic of paralleling deparalleling control

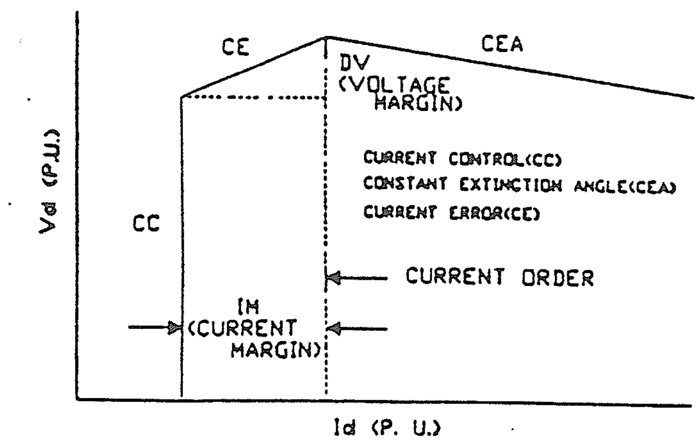


Figure 1.3: CEA, CC, CE characteristics

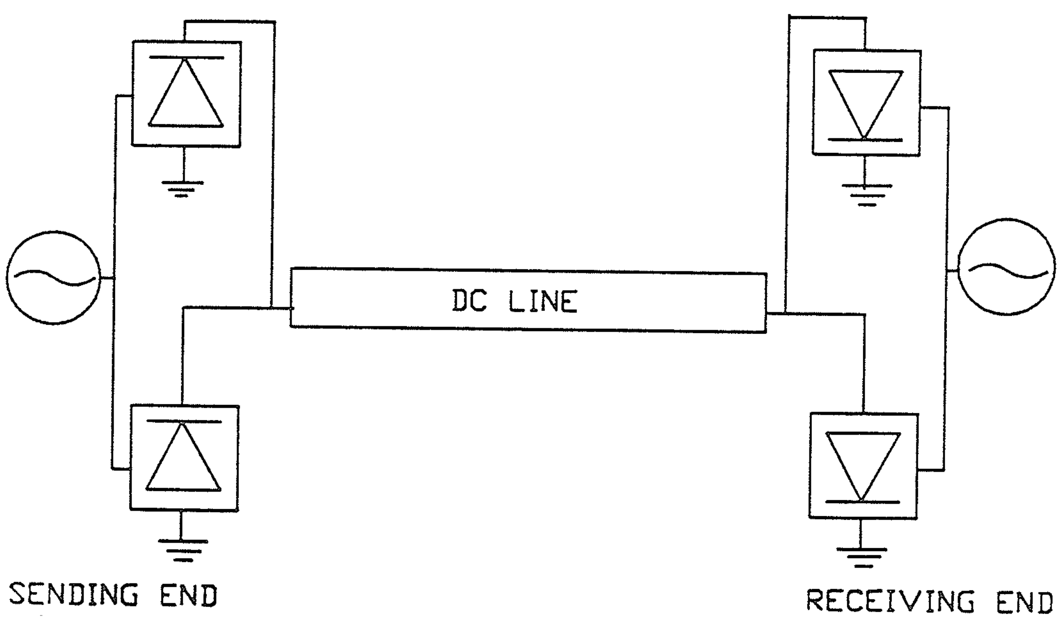


Figure 1.4: Two rectifiers and two inverters in parallel

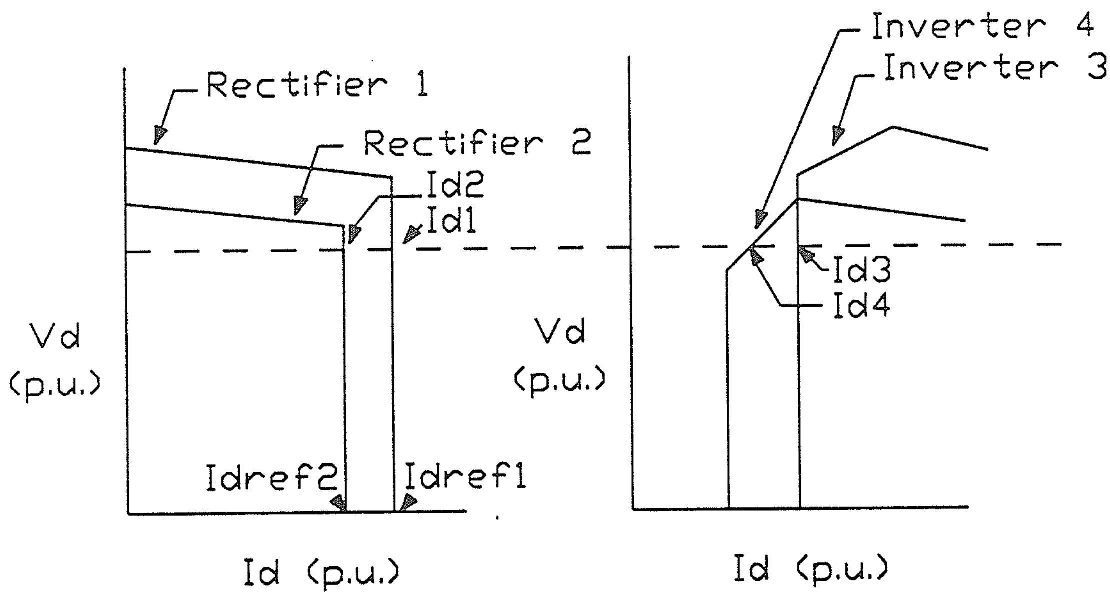


Figure 1.5: Multiterminal characteristics

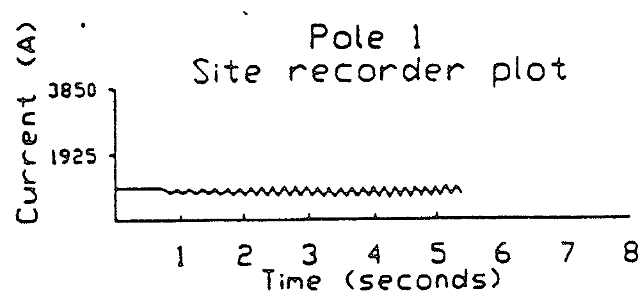


Figure 1.6: Hathogram recordings of pole 1 direct current

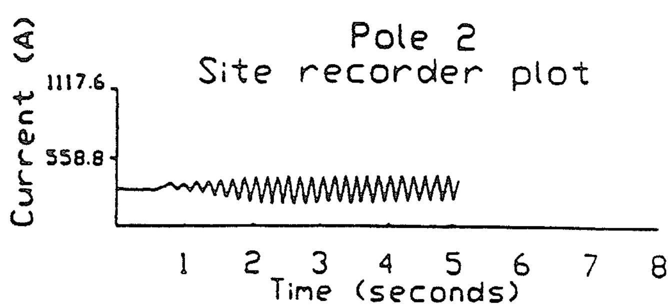


Figure 1.7: Hathogram recordings of pole 2 current

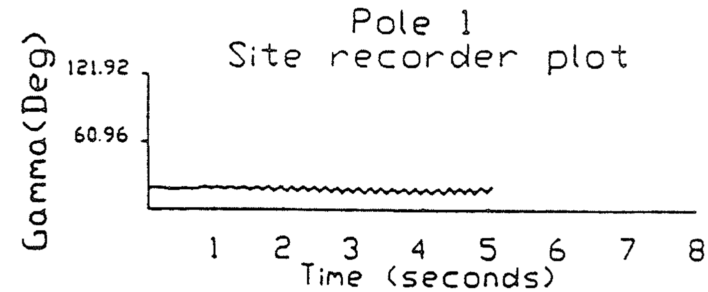


Figure 1.8: Hathogram recordings of pole 1 extinction angle

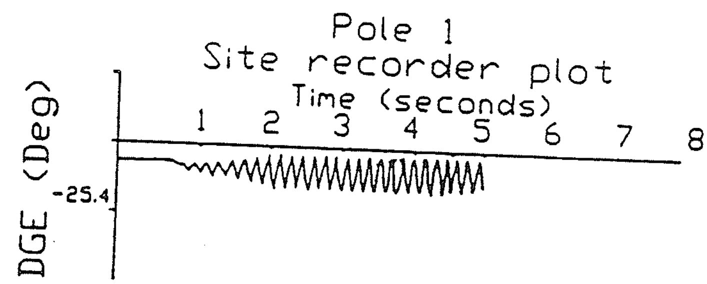


Figure 1.9: Hathogram recordings of pole 1 current error

1.3 Survey of Previous Work

As early as 1951, Busemann [7] explained the hunting phenomena of a rectifier supplying an inverter through a transmission line under constant current control. He found that under certain conditions hunting occurred at half the firing frequency, and derived a formula for the critical equivalent gain of the rectifier under current control leading to instability.

Bjaresten [8] and Fallside et. al. [14] modelled the rectifier as a pure sampler, and were able to derive respectively a closed form and an infinite series form of the critical gain of the closed loop system leading to instability at half the firing frequency. Fallside even used describing functions to study the instability for large disturbances.

Hazel et. al.[18] modelled the converter as a sampler followed by a zero order hold. This mis-represents the converter behaviour and leads to very conservative results, when applied to the prediction of instability. Later, Hazel developed a general theory for converter system, which has not been experimentally confirmed.

With the exception of Bussmann, all other researchers neglected the existence of a finite commutation time due to the presence of leakage reactance in the converter transformer. They also assumed that the converter is connected to an infinite ac bus, thereby neglecting the ac network impedance.

Sucena-Paiva et al. [35] were successful in removing the restriction of zero commutation angle and developed a linearized discrete model, which represents accurately the intermittent control action of the converter with a finite commutation angle. It was shown that this commutation angle played a major role in the dynamic behaviour of the converter under closed loop control. The Z transform method of analysis was used to calculate stability boundaries which was successfully confirmed on an HVDC simulator. However, this is a linearised model and does not include the full behaviour of converter representation. When the converter is connected to an ac system, the discrete model alone is not capable of representing the dynamic behaviour of the converter as the ac bus voltage is now a dependent variable. Further, as the filters are designed with high quality factors, parallel resonances occur at certain frequencies with the result that a high impedance is encountered by currents of these frequencies injected by the converter into the ac network. To model the interactions between the ac and dc system quantities, the modulation and demodulation characteristics of the converter operation has to be taken into account. This inherent modulation process is unique, exhibiting only vague resemblance to the modulation and demodulation process encountered in the communication field.

Persson [31] introduced the concept of carrier functions, which are in fact the carrier functions of the modulation and demodulation process, to calculate the transfer function of a converter taking into account the effect of finite ac network impedance. Although this technique is similar to the describing function, he limits his analysis to small disturbances. Susana-Paiva and Ferris [34] followed a similar path, but used sinusoidal carrier functions, an approximations that reduced considerably the computational requirements without the significant loss of accuracy. In both processes, only the onset of instability can be predicted, since linearized model are used, frequency domain techniques are employed.

Sakurai et el.[43] used describing function approach to analyze a particular mode of harmonic instability detected in the Skai- Skimano frequency converters, which is characterized by a fundamental frequency oscillations on the dc side and a 2nd harmonic oscillation on the ac side. This mode is likely to occur if the dc system resonates near the fundamental frequency , and if, the combined ac network plus filter impedance has an antiresonance between the 2nd and 3rd harmonic as is the case in the HVDC links.

Jotten et al. [21] describes the influence of resonances on the dc side and antiresonances on the ac side, if the dc resonance and ac antiresonance frequencies are related by the modulation process inherent to the converter. Instability in the current control loop might occur, if the controller is given a high gain and bandwidth. The frequency of the resulting oscillation will be close to one of the lower harmonic frequencies.

Olivera and Yacamini [51] [52] developed a program to calculate ac and dc harmonics in converter systems with both ac and dc impedances. Using an iterative method, the final pattern of the harmonic in the ac bus voltage, ac current, dc voltage and dc current, with and without current control are evaluated. If the iterative process fails to converge, the authors conclude that they are in the process of harmonic instability. As no test results are provided, it is difficult to confirm whether we are in the presence of a true or numerical instability.

Yacamini and Smith [53] computed the negative sequence impedance of converters by applying an unbalanced voltage supply to the converter system and measuring the resultant ac line current. They showed that the negative sequence impedance depends on the type

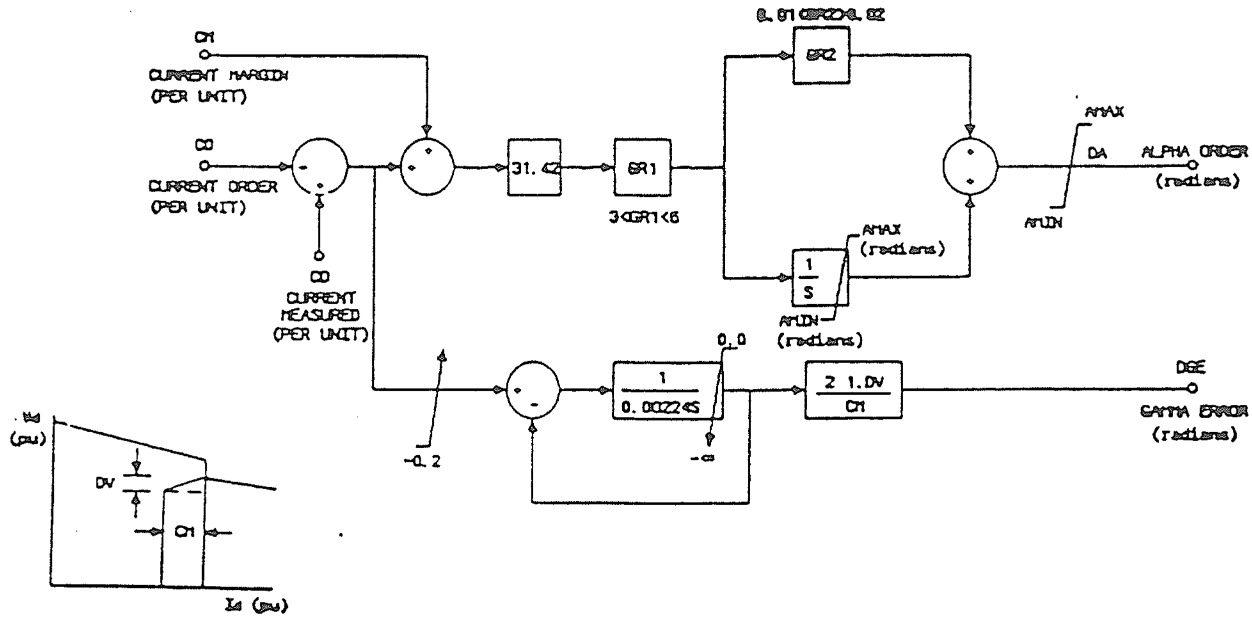


Figure 1.10: Generic pole controller

of firing system used, and concluded that Phase Locked Loop (PLL) based firing system is advantageous, as it leads to a higher negative sequence impedance.

The saturation of the converter transformer core due to spurious dc components can also contribute to harmonic instability, as noted by the Ainsworth [5]. This particular type of instability is caused by a combination of weak ac system and a resonance near the fundamental frequency on the dc side, and as suggested, this phenomena may be present even without saturation. Core saturation, however, does aggravate this phenomena.

1.4 Scope of the Thesis

The purpose of this thesis is to adjust converter control of the multi-terminal HVDC transmission system, so that 6 HZ inter-bipole oscillations were removed from the system [40]. However, the problem lies at not having accurate control models of Nelson River HVDC system. Many power system simulation programs however do provide generic models for the control system.

For example, the generic current controller (or Pole controller) from EMTDC is shown in the figure 1.10. Many of the essential control blocks are represented in such a generic block. For example in the figure 1.10, a proportional integral (PI) controller adjusts the firing angle order alpha in response to the difference between measured and ordered current. A second path with the signal DGE at its output is used to change the extinction angle (γ) reference

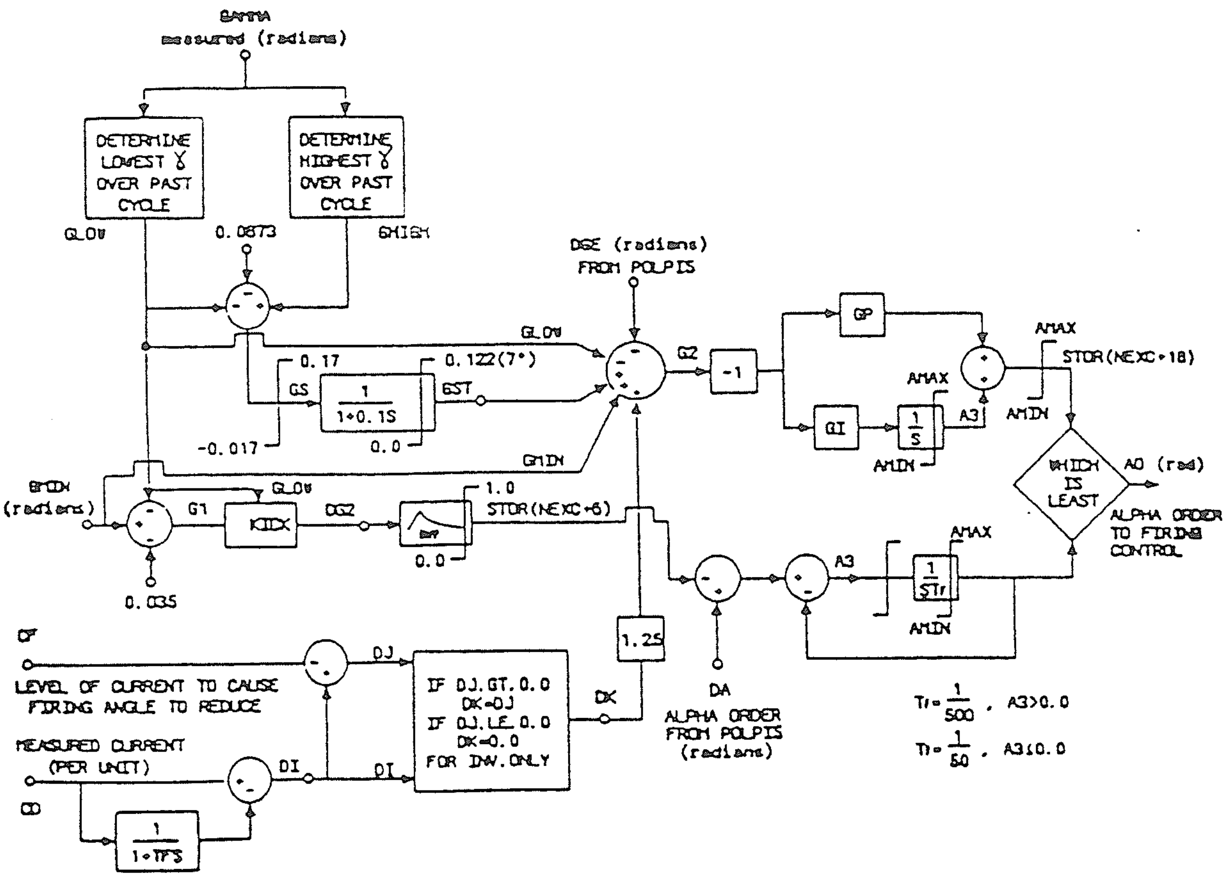


Figure 1.11: Generic valve group controller

in the subsequent valve group controller in order to obtain chamfered- current error control-characteristics. Note the converter characteristics as shown in figure 1.3 and in fig 1.10.

A few attempts at modelling can be made trying to fit the real controller with the generic block diagram. This usually leads to an improper representation because there may be extra blocks and other signals in the real control system, or there may be switches that change from one set of controls to another.

Nevertheless, the multiterminal HVDC system as shown in figure 1.1 was simulated with the EMTDC generic controls and figures 1.12, 1.13 and 1.14 show the resultant current in the inverters and the common rectifier(both rectifiers were combined into a common rectifier). It is seen from the above graph that there is no oscillation , although in reality, there is a six hertz oscillation between the two converters labelled BP1 and BP2.

The above results corroborate the fact that it is not possible to simulate the six hertz interbipolar oscillations between inverter one and two with the help of generic control. More accurate and detailed control system modelling is required.

Accordingly, this thesis is logically divided into three sections:

1. Accurate modelling of the HVDC controls that are being used in the Manitoba HVDC system.

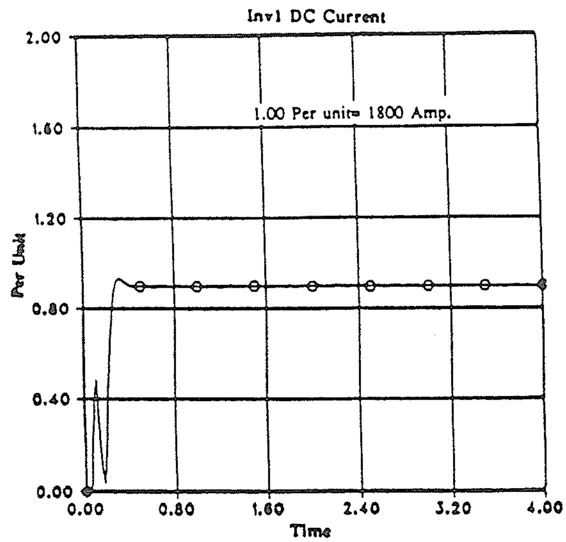


Figure 1.12: Simulation results obtained with generic controller: inv1 current

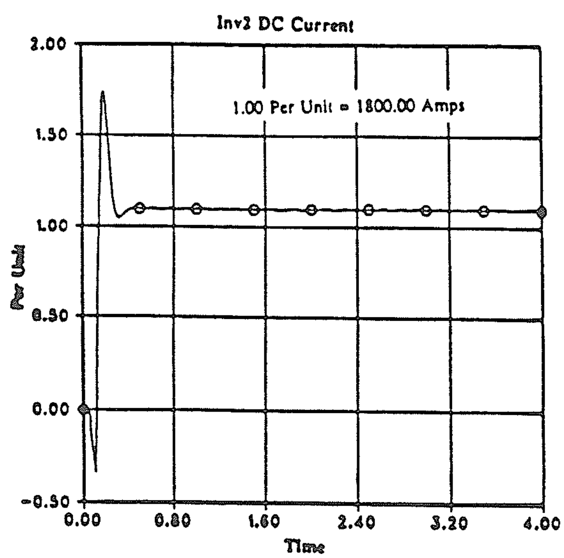


Figure 1.13: Simulation results obtained with generic controlleri: inv2 current

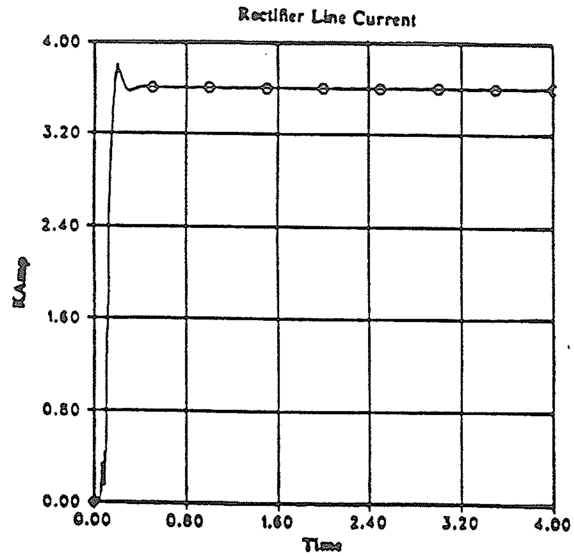


Figure 1.14: Simulation results obtained with generic controller: rectifier line current

2. Adjustment of the parameters of the feedback control loops that has small or negative gain and or phase margin, so that increasing gain and or phase margin will hopefully remove the oscillations.

3. Development of the nonlinear control system analysis technique–the Describing Function in an attempt to analytically predict the existence of the limit cycles of the system and suitable means to get rid of them.

Since this research project was externally funded, there was an urgency to get a suitable solution to the interbipolar oscillations problem. Hence the somewhat brute force method of time domain digital simulation was used to simulate the phenomena and suggest control modifications to eliminate the oscillations.

Later extensive literature survey was carried out to identify the suitable analytic techniques, and the describing function was found to be suitable for this particular problem at hand [12]. In this thesis, the EMTDC digital transients simulation package has been used to simulate the instability phenomena and has been succesfully applied to the elimination of the instability. The thesis describes how to select a system model that is sufficiently simple but not oversimplified so that these phenomena can not be studied. The thesis also discusses an approch to the use of anlytical techniques such as the describing function method to the study of multiterminal dc control problems. The latter material is discussed at a theoretical level because the detailed application of such methods was not possible within the scope of this thesis.

1.5 Conclusion

Analysis of dynamics of the non-linear control syystem is complex, but never the less feasible. Of all the analytical techniques suitable for nonlinear system study, the Describing Function turns out to be the most appropiate for multiterminal HVDC system Study. Off-line digital simulation programs such as EMTDC when judiciously used in conjunction with the nonlinear analysis technique forms a very powerful and effective tool for nonlinear system study. Caution must however be exercised that the model that is being used to study the system must accurately correspond to the real and not some pre-defined generic model of the system. This is however only to be expected. Accurate modelling down to the electronic component level is necessary. In addition, extreme care must be exercised to evaluate the transfer characteristics of the control amplifiers. In other words loading due to following stages's input impedance and similar phenomena should be take into account while deriving the dynamic characteristics of the controller. This is once again is only to be expected. Hard limits, dynamic range of the signal at the output of such operational amplifiers, drift, slew rate, common mode rejection ration, linearity and frequency response of the intrinsic operational amplifier must be take into account when we are trying to evaluate the dynamics of the controller.

Chapter 2

Multi-terminal Operation and Control

2.1 Introduction

In this section, the concept of parallel multiterminal operation of HVDC converters is discussed. The physical aspects of paralleling are also discussed. A detailed discussion of the control concepts behind the paralleling operation, including the sequence of events required to place a pole into parallel operation are discussed. Examples of various paralleling schemes are discussed. The purpose of this chapter is to familiarise the reader with the terminology and operating concepts required for the understanding of the simulation in the study.

2.2 Multi-terminal Transmission links

Multi-terminal operation of converter is desired since it allows the connection of various converters in parallel to a single transmission lines, as shown in the figure 2.1 for the three-terminal transmission line. In two terminal transmission line, we allocate the current margin

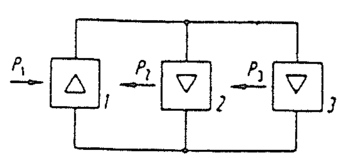


Figure 2.1: Parallel connected three terminal dc transmission links.

physically to one of the two stations, preferably the inverter station, and the question is now what should be done, when there are several inverter stations. The allocation of the current margin ΔI to a particular station is out of the question, since this station may not be operating, and the margin would not be active. Let us call the currents of the individual inverter stations be I_x and the different current orders to their controllers i_x. let both of these be positive when relating to a rectifier and negative for an inverter. We than have

$$\sum I_x = 0 \tag{2.1}$$

By contrast to this, we ensure that the following conditions is maintained for the control orders

$$\sum i_x = \Delta I \tag{2.2}$$

Naturally, only currents contributing to the equation 2.1 maybe included in the equation 2.2. If in the two terminal transmission line, we regard the margin input to the current controller as belonging to the current order, equation 2.2 also applies to this case. Figure 2.2 shows that the mode of operation is closely similar to that of the two-terminal transmission line. As in the case of two transmission line, the station with the lowest voltage ceiling determines the transmission voltage (A), while the others follow their current controllers(B). The figure 2.2 is based on the presence of two rectifiers (1 and 2) and two inverters (3 and 4). In the upper part of the figure, the voltage is determined by an inverter (4), and in the lower part of the figure a rectifier (2) determines the voltage. The margin is already active in the voltage-determining station and results in a current greater than the current order by ΔI when that station is an inverter and by a reduced current when it is a rectifier.

Every connection and disconnection of a converter must be linked to a corresponding change in the current orders, in order to fulfil equation 2.2. Similarly the order for one converter cannot be changed without the corresponding adjustment of the others. This task is therefore best entrusted to a central order point, which receives all information on the operating conditions in the stations and on the desired transmitted powers, and issues corresponding orders to the individual stations taking into account equation 2.2 as well.

When a converter is switched off, its current is first reduced to zero. As before, a rectifier can be blocked. In the case of an inverter, we must first ensure that it is not determining the voltage. This is achieved by using its tap changer to set a sufficiently high voltage. Disconnecters are then able to isolate from the network the converter, which is carrying no or non-continuous direct current.

As in a two-terminal transmission link, faults in the converter stations or the network are cleared by blocking the rectifier stations. A particular problem arises from a short circuit in an inverter station, if its nominal power is small relative to the total power. In order to avoid overloading, especially in the case of Thyristor valves, the d.c. reactors of such stations are given large inductances , so that the current rise during the time required for fault clearing is limited.

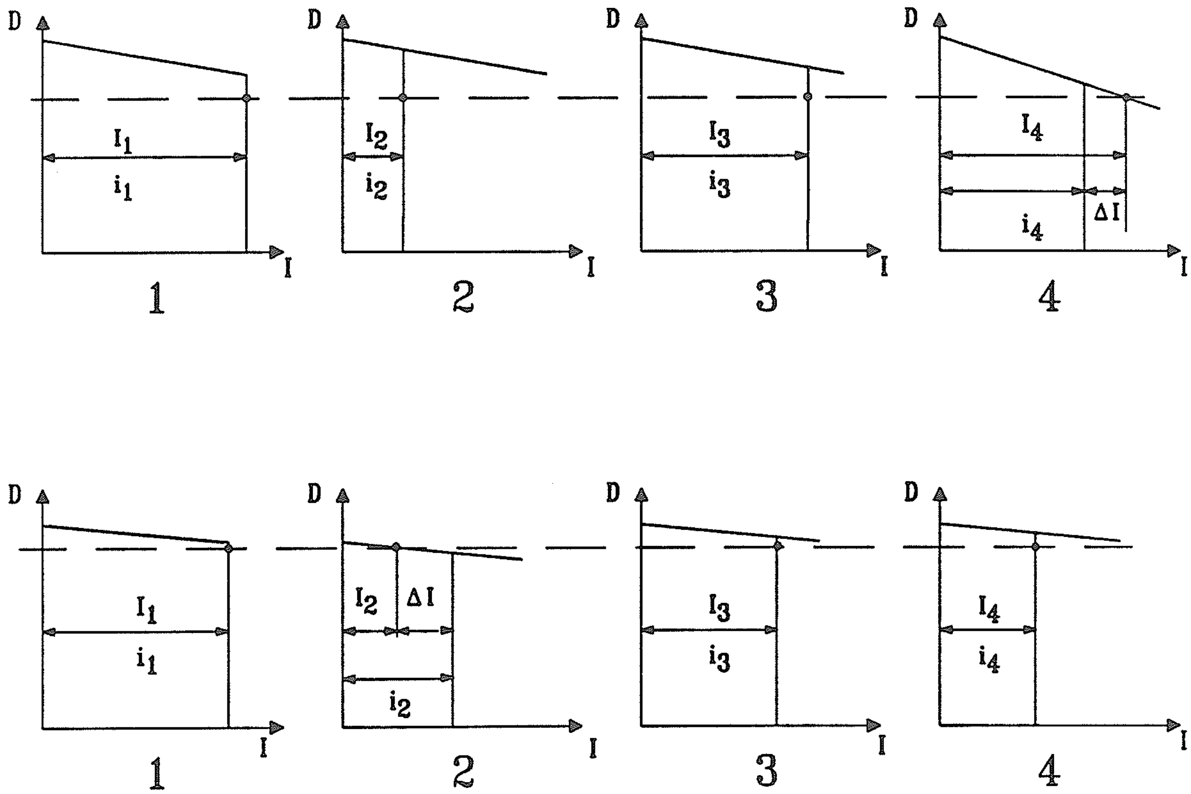


Figure 2.2: Converter characteristics of a four-terminal transmission link with two rectifier stations (1 and 2) and two inverter stations (3 and 4.)
I Direct current; i Direct current order; ΔI current margin; A working point of voltage-determining converter; B Working points of current-determining converters. voltage determined by inverter 4; Bottom: Voltage determined by rectifier 2.

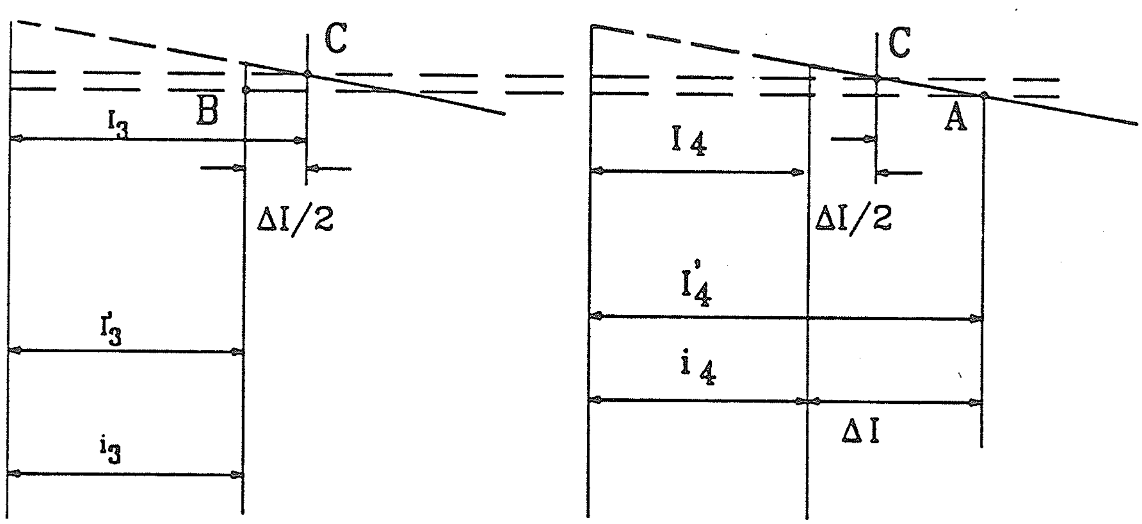


Figure 2.3: Parallel connection of converters at the same station.

2.2.1 Parallel Converters in the Same Station

In a constant voltage station, two bridges must be connected in series to form an inseparable twelve pulse unit; this is generally advantageous from the ac side filter design. Such units are generally designed for the entire direct voltage, and the station power will be distributed over a number of these units, connected in parallel to the dc network.

The parallel connection of the units can then be regarded as a multiterminal transmission link, and the considerations set out above apply to it as well. The fact that the parallel converters are arranged together in one station can be used to bring about an improvement explained in the figure 2.3 above. Figure 2.3 shows the characteristics of two converters connected in parallel. As before, the inverter with working point A is voltage determining and assuming $i_3 = i_4$, has a current greater by ΔI than that of the inverter with working point B. A balancing addition to the current control, called the current balance signal, can be used to equalize the currents carried by the units in one station. A margin $\Delta I/2$ is added to both inverter's current controller thereby shifting the constant current characteristics of both to the right of the orginal working point. Working point C then applies for all units instead of working A and B, that is, the transmission voltage is not determined by the individual converters, but by the converters together, and they share the margin equally. Figure 2.3 also shows that the power factor is slightly improved by this current balance controller action. More important is the fact that all the paralleled units are fully exploited as regards their current capacity. However, the working point C is unstable, and the balancing arrangement that must hold it stable, must act very quickly. This is the reason why the process requires all the converters to be at the same station.

2.2.2 Power Reversal

In two terminal system power reversal is achieved by changing the firing angles of rectifier and inverter to give negative voltage on each converter. Polarity change in the system is out of the question in multiterminal transmission links, and a station which is to operate sometimes as the rectifier and at other times as an inverter must be equipped with a polarity reversing switch. In bipolar installation reversal can be achieved by simply changing the converter connections to the two lines. however, the polarity reversal is achieved by mechanical devices; it will be carried out when no current is flowing, and disconnecters can be used for this purpose.

2.3 Multi-terminal HVDC Link Controls

Conceptually all HVDC control schemes are similar and consists of the following

1. Master Controller or the Power flow controller.
2. Current Controller or the Pole Controller.
3. Extinction Angle Controller or the Valve Group Controller
4. Three-phase Phase Locked Loop (PLL) based valve firing circuits.

The following figures explain the operation of these controllers schematically.

2.4 Master Controller

As shown in the figure 2.4, 2.5, 2.6, the input to the Master Controller (MC) comes from the Load Dispatch Office (LDO). MC controls the complete bi-pole, thus it produces four outputs for the two terminal bipolar system– one to each pole via telecommunication as an input to each pole controller.

The input from the LDO along with the following signals is processed by the MC [46]

1. Load frequency control change.
2. Frequency change of the receiving and transmitting ends. This is mainly due to disturbances.
3. Phase change of the receiving and transmitting end. This essentially represents system load change.

The purpose of the MC is to accept the above signals and vary the magnitude of power that is flowing through the system. By virtue of this controlling action MC helps to stabilize the ac system.

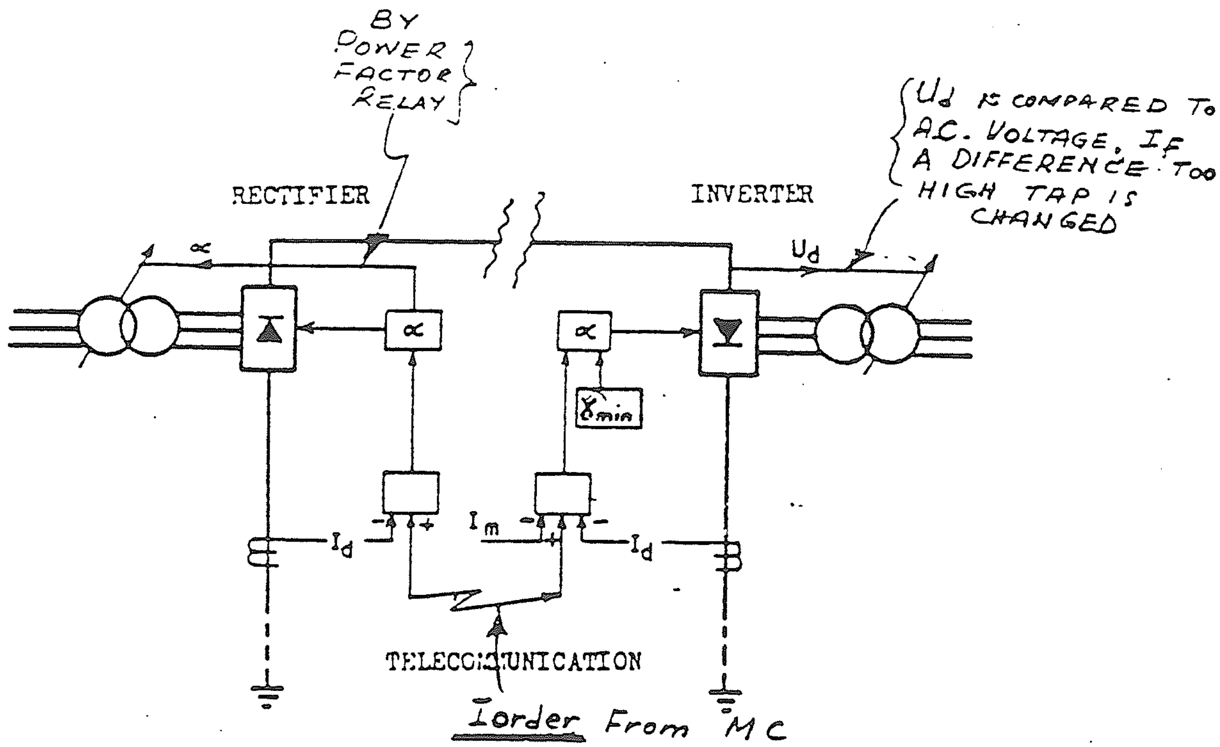


Figure 2.4: Schematic diagram of the overall HVDC control[46]

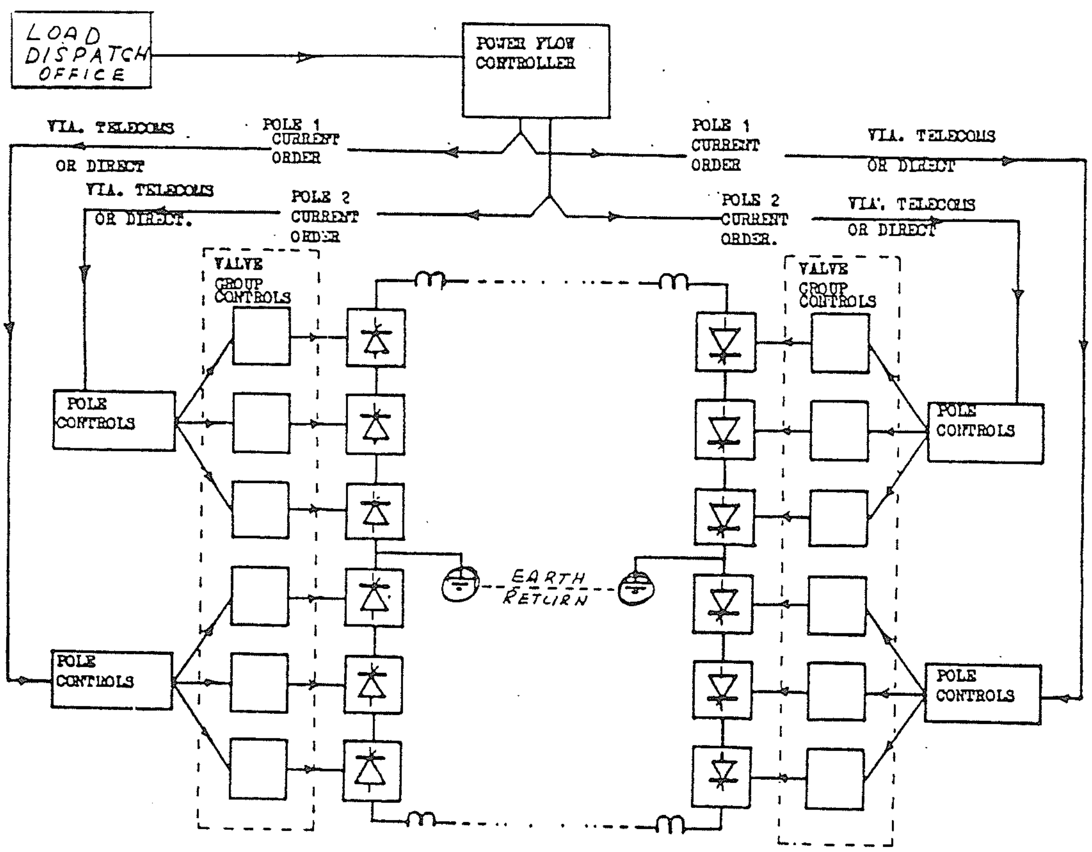


Figure 2.5: Schematic diagram of the master control[46]

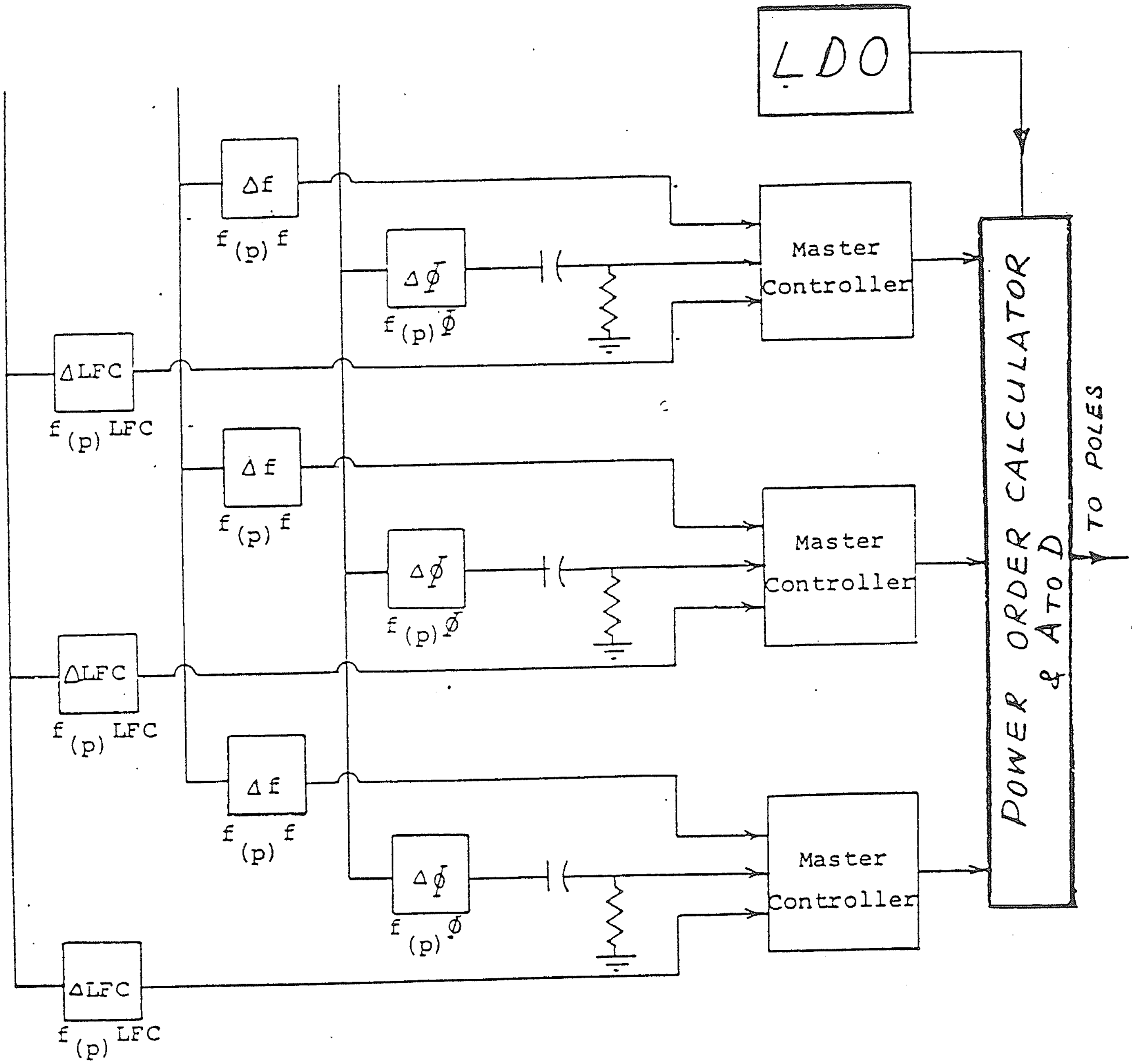


Figure 2.6: Input from ac system to master control[46]

2.5 Pole Controller

The schematic diagram of the pole controller is shown in figure 2.7. This is essentially a proportional plus integral controller with a hard limit on the output α. The three inputs to the pole controller are

1. Current order obtained from the Master Controller via Telecom.

2. Current Margin–this is usually 10-15 percent of the of the rated current capacity of the pole.

   The seting up of this parameter depends on the following, and they are as follows:

   (a) Whether current balance controller is used or not.

   (b) Whether multi-terminal operation is used and

   (c) The slope of the current error characteristics.

3. The measured direct current of the pole- this is obtained from the Direct Current Transformer(DCCT) of the pole after suitable filtering.

The important point to note is that since integral control is applied for the pole controller, steady state error is zero.

2.6 Valve Group Controller

The schematic diagram of the valve group controller is shown in figure 2.8. The output of the pole controller, as a measure of firing angle α, goes to the Valve Group Controller. The responsibility of the valve group controller is to compare the α from the pole controller to the extinction angle γ and to select the minimum of the above two. In essence, the top control path of the valve group controller is used for the constant extinction angle control, and the bottom control path is used for the current control. The output of the Valve group controller is fed to the three-phase Phase Locked Loop (PLL), which delivers firing pulses to the thyristor bridge.

2.7 Phase Locked Loop

The purpose of the three-phase Phase Locked Loop (PLL) [44] is to accept the output of the valve group controller and produce the firing pulses in synchronization with the ac system bus. Since the ac voltage on the valve side is highly distorted and noisy, the primary side ac voltage is used in the three-phase PLL operation.

There is a large variety of three-phase PLLs reported in literature and in actual implementation. The interested reader is advised to refer to [44] and [4] for complete details. As a rough estimate, if we assume the three-phase PLL as a first order system, we can talk about the synchronization time constant.

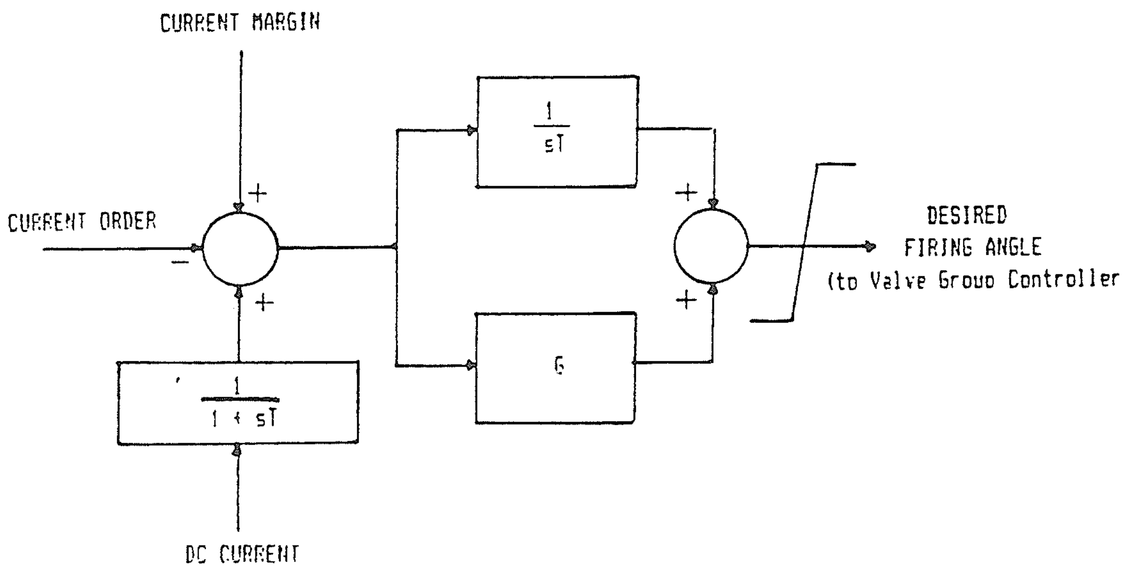


Figure 2.7: Schematic diagram of the pole controller

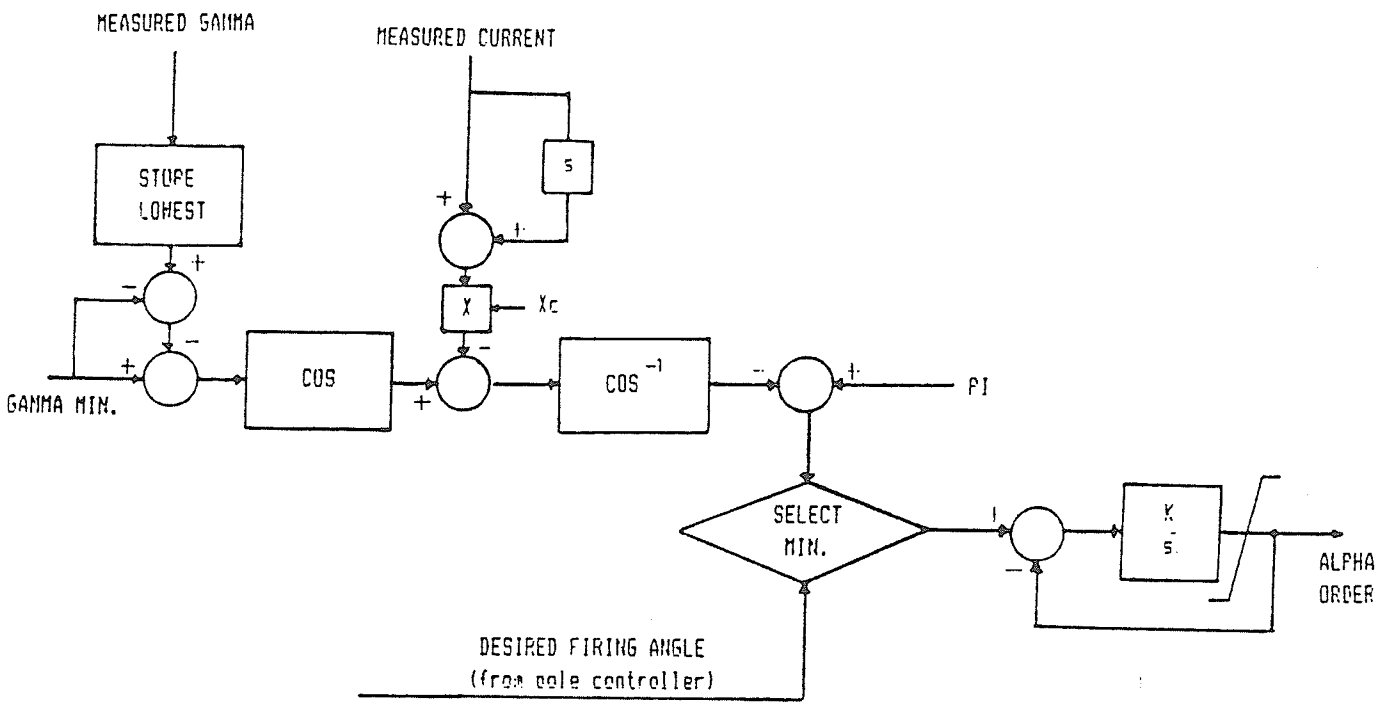


Figure 2.8: Schematic diagram of the valve group controller

In addition to the above controls, the HVDC controls also includes Current Balance Control, which is used to achieve an even balance of the load current among the HVDC poles of a station. The Current Difference Control is similarly used to share load current of a station in a pre-defined manner among the poles of a HVDC station.

Chapter 3

Modelling and Simulation

3.1 Introduction

In this chapter, a description of how accurate system modelling of a dc system with an electromagnetic transient simulation program can be used to study and correct interbipole oscillations between converters connected into a parallel multi-terminal system is given. This chapter shows how to decide on the detail of modelling that is required, and demonstrates that it is often not enough to use prepackaged, generic HVDC control models, supplied with these programs. The detail of control models that are used in the electromagnetic simulation programs are shown to have a significant impact, in some cases, on the simulation results. In particular, a case of six hertz oscillations, in the dc currents of two converters on the Nelson River System, is accurately simulated, and it is shown that control modifications suggested by the simulation actually do eliminate the interbipole oscillations.

3.2 Methodology

Digital programs for simulating transients in HVDC systems and controls have been developed in the past few years [33],[49],[17],[29]. These programs have been used in many general studies to evaluate different control strategies and to study new types of converter circuits. Nyati [29] has used such a program to compare the effect of various voltage control devices at converter terminals. Arabi [3] has looked at different firing strategies for series-tapped HVDC systems. Turanli [45] has studied forced-commutated converters. In most of these studies, generic models of controls were used, and the conclusions of the studies were of a general nature, and not related to any specific operating system. Relatively little has been reported on comparisons between the field tests and the results produced by digital simulation software. Woodford [50] and Ino [20] have made some such comparisons to show that these programs can accurately reproduce the observed results from the field.

In general, sufficient experience has been obtained with HVDC system simulation to be able to use the program for analyzing disturbances and setting control parameters on operating dc systems. In this thesis, we have set up such a model on the EMTDC transient simulation program for the controls and converters of Bipoles 1 and 2 of the Nelson River HVDC transmission system. EMTDC was used to find control settings for the converter controls to eliminate a low frequency inter-converter oscillation. While carrying out parallel operation tests at Manitoba Hydro, it was observed that when inverter 1 converter transformer tap setting was 4 % higher than the inverter 2 converter transformer tap settings , an oscillation would develop in which one inverter took more current, for a half period, at the expense of the other. For the next half period (of approximately six hertz frequency), the other inverter took more current. The total current put out by the paralleled rectifiers was constant. It should be noted that the two bipoles were supplied by different manufacturers, and have different controls. It was found that to duplicate the six hertz oscillation using digital simulation, it was not sufficient to use the generic control blocks provided in the EMTDC simulation program. Detailed modelling, almost at the electronic circuit level, was essential.

Many different strategies to solve the problem were investigated, using the EMTDC program, and the easiest appeared to be in the form of changing the time constant of a first order pole control block. In the real system, this was achieved by changing a capacitor to the value suggested in the simulation, which corrected the problem. It was also observed that a different value of capacitor would be required, if one smoothing inductor was out for maintenance. This too was verified in the field.

Thus it is possible for utilities to develop their own system models in-house, using commercially available simulation programs. After some manipulations, between tuning the digital model and field tests, the model, then, can be used as a reliable guide to modelling the controls for other system contingencies.

3.3 Inter-bipolar Limit Cycle Oscillations

The Nelson River HVDC system of Manitoba Hydro, shown schematically in Fig. 3.1, has two bipolar dc circuits, which bring power from the generating stations on the Nelson River to the southern load centers over roughly 900 km of terrain. The first circuit, Bipole 1, is rated at 463.5 kV, 1800A, and has three 154 kV mercury-arc valve group per pole. Bipole 2 is rated at 500 kV, 1800A, and has two 12 pulse thyristor valve groups per pole. Control modifications have been implemented, and high speed switches provided to allow parallel operation of the converters on any one pole on a single transmission circuit, in the event of the unavailability of the other transmission line. The initial paralleling was carried out at low voltage- with one 154 kV Bipole 1 six pulse valve group paralleled to one 250 kV Bipole 2 twelve pulse valve group- to prove control concepts and modifications. During paralleling operation, the 250 kV valve group is operated at a lower voltage, so that both valve groups have the same voltage. These tests were carried out in the summer of 1982 [6]. High voltage paralleling- with the full 463.5 kV of Bipole 1 and one 500 kV pole of Bipole 2- were carried out in 1985 and 1986. The block schematic of the paralleling controls is shown in Fig. 3.5. The paralleling logic-block coordinates the closing of the high speed switches, and also assigns the correct current orders to the current (pole) controllers of the poles that are paralleled.

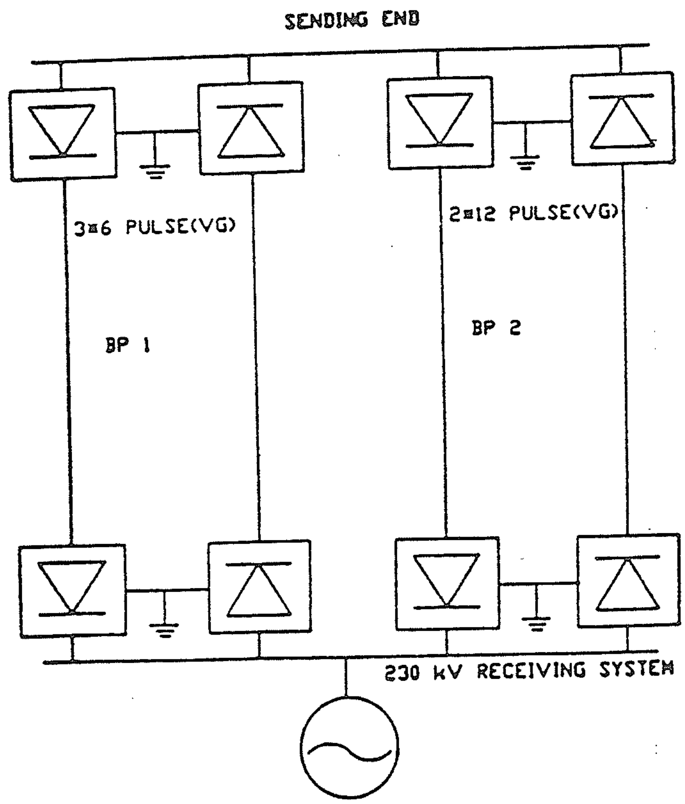


Figure 3.1: Nelson River transmission system

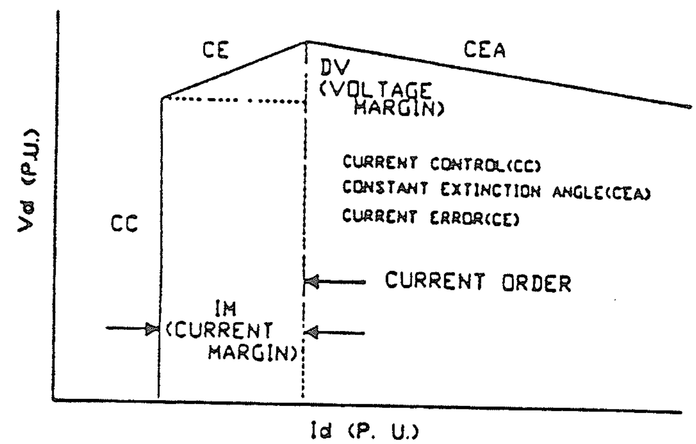


Figure 3.2: CEA, CC, CE characteristics

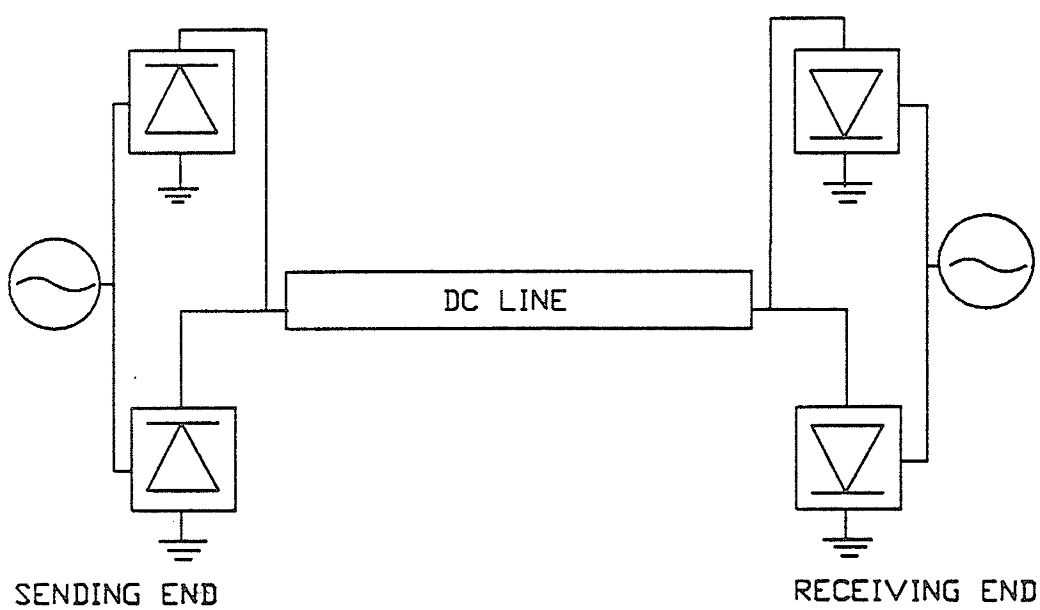


Figure 3.3: Two rectifiers and two inverters in parallel

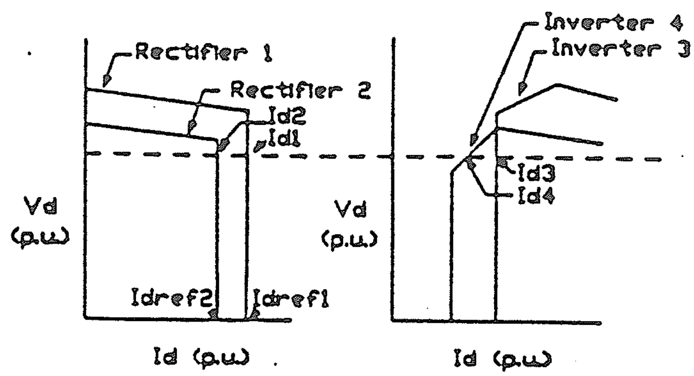


Figure 3.4: Multiterminal characteristics

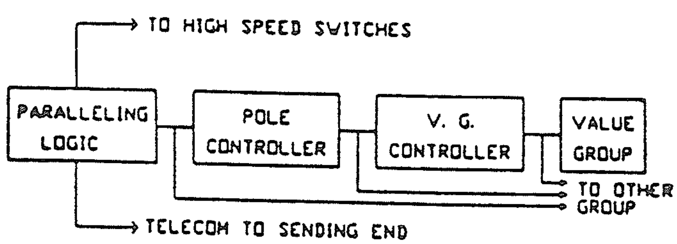


Figure 3.5: Schematic of paralleling deparalleling control

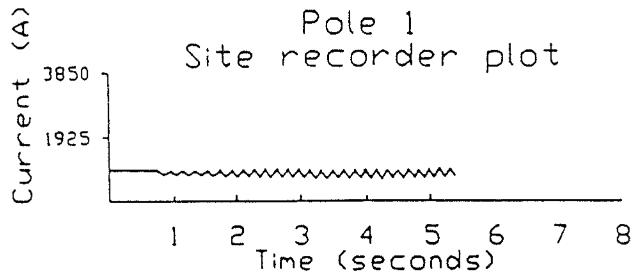


Figure 3.6: Hathogram recordings of pole 1 direct current

The valve group control-block either passes on the pole controller's firing angle order, or selects another firing angle- based on whether there is need for other forms of control such as: constant extinction angle control or current error control. Fig. 3.2 shows a typical inverter characteristic outlining the meaning of CEA, CC and current error (CE) control. By changing the tap changer ratio, the inverter characteristics can be made to intersect the rectifier characteristic in any one of these three modes. Fig. 3.3 shows two inverters and two rectifiers operating in parallel. As the rectifiers' uncontrolled characteristics are at a larger voltage than the inverters' characteristics (Fig 3.4), the rectifiers are in constant current control, with Id1 and Id2 respectively.

The common voltage line (dotted) intersects one inverter in the CE characteristic, and the other on its constant current characteristic. (By Kirchoff's current law (KCL) Id1+Id2=Id3+Id4). Note that further dropping of the ac voltage (by tap changer control) on inverter 4 will result in its going into CEA operation. Note that exactly one of the four, say inverter 4, is in a voltage control mode (CEA) and absorbs the spill over current . During paralleling tests in 1985, it was observed that a mode of operation was possible with the rectifiers in stable, constant current operation, but with the inverters having a six hertz current oscillation . Fig. 3.6, 3.7, 3.8, 3.9 show field recordings of this phenomena. The oscillation only occurred with the inverter of Bipole 2 in current error control and the inverter of Bipole 1 in CEA control. If the tap-changer-ratio of Bipole 2 were increased, so that it went into constant current operation, the oscillation would cease.

It was observed that the dc line current (sum of two rectifier currents) was constant without oscillations. Thus the rectifier did not seem to play a role in the phenomena. Also, the ac side bus voltage on the inverter appeared to be sinusoidal and essentially free of low frequency oscillations. Thus there appeared to be no relationship between these oscillations and the ac side systems.

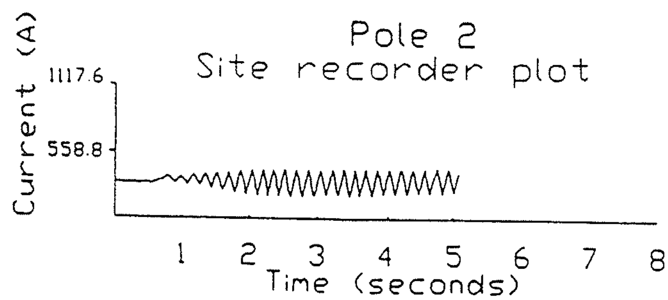


Figure 3.7: Hathogram recordings of pole 2 direct current

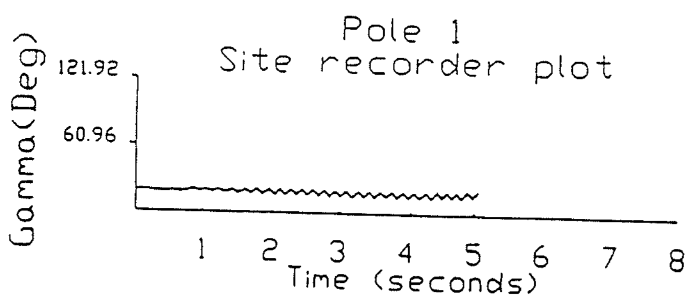


Figure 3.8: Hathogram recordings of pole 1 extinction angle (gamma)

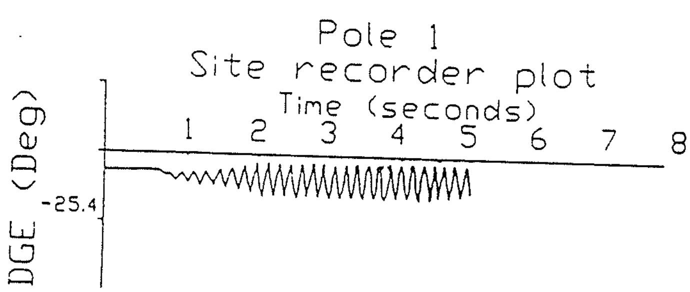


Figure 3.9: Hathogram recording of pole 1 current error

3.4 System Modelling

3.4.1 Modelling of the HVDC System

Although a highly detailed model of the dc system and some of the associated ac system has been developed using the EMTDC program, it is important to find a simpler system for study. Modelling a smaller system saves considerable computation time. The system must be simple, but should not be oversimplified to the point where the phenomena to be looked at can no longer be represented.

It was observed that the ac side voltage on the inverters was a nearly harmonic free 60Hz balanced waveform. It was thus decided to model the ac bus as a 230 kV infinite bus. The converter transformers were modelled in three phase detail to account for the non-zero commutating inductance.

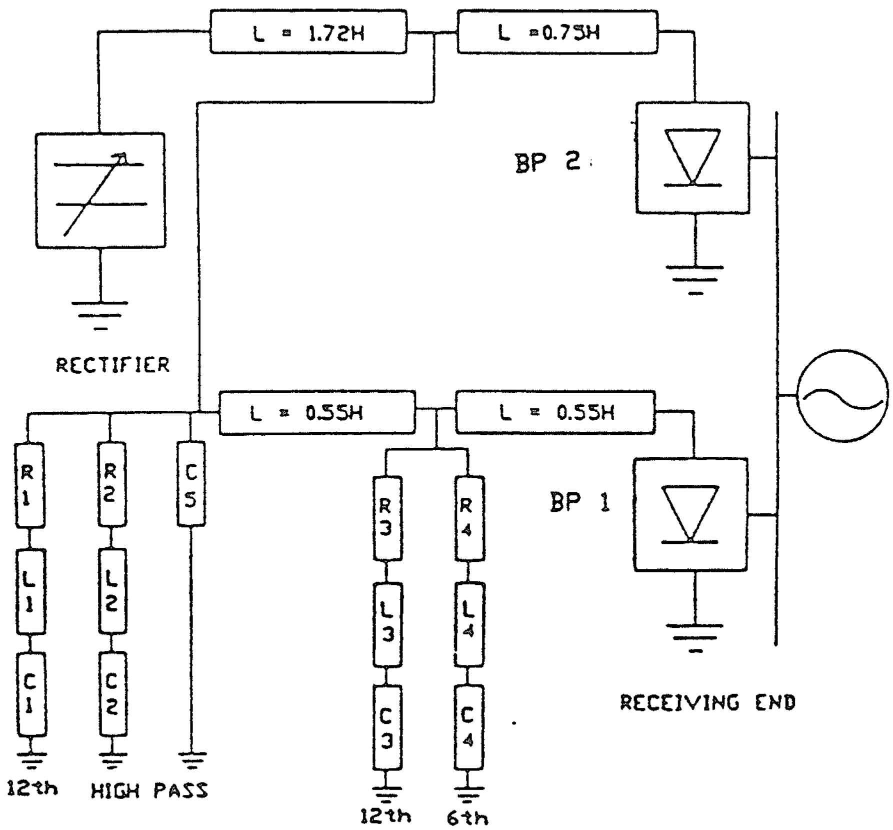
The inverters were modelled as six pulse valve groups. The higher harmonic behaviour was not being studied, and so the more accurate 12 pulse representation was deemed unnecessary. Also, the extra harmonics would not add harmonic voltages to the ac bus because it was modelled as an ideal voltage source. Similarly, although some 6th harmonic ripple current would now show up on the dc side, the important phenomena being looked at here was the large low frequency oscillations of the dc current. We were, however, prepared to make the representation 12 pulse if the initial studies showed us that this was necessary. It was decided to model the two rectifiers in parallel as a single dc voltage source behind a Thevenin resistance. The voltage source was controlled by a complete set of dc controls (identical to those used for the full converter model) and included the non-linearity relating the dc voltage to the firing angle . This simplified model was again chosen, as the harmonic behaviour was not important in this study.

The dc side filters and smoothing reactors were represented in full detail. The inductors and filters affect the transfer functions relating the dc currents and the converter voltages, and are therefore required in the model. Similarly the dc line was represented as a lumped inductance for this low frequency study.

Finally, only a monopolar representation was chosen, because the other poles of the opposite polarity operated quite independently. Fig. 3.10 shows a schematic of the minimum system developed for this study. It is evident from Figure 3.10 that the sending end rectifiers of figure 3.3 have been clubbed together as a single, controlled voltage source, and the rectifier side smoothing inductors and the line side inductances are now represented by a single 1.72 H inductance. The 12th and high-pass filters of BP2 and the 6th, 12th and high-pass filters of BP1 are properly represented on their respective buses. Note also, the 0.75H smoothing inductance of BP2, and the split 0.55H smoothing inductance of BP1.

3.4.2 Modelling of the HVDC Controls

Many power system simulation programs include generic models for converter controls. For example, the generic current controller (or pole controller) from EMTDC [10] is shown in Fig. 3.11. Many of the essential control channels are represented in such a generic block. For



R1=7.94Ω R2=100.00Ω R3=5.50Ω R4=4.42Ω

L1=0.122H L2=0.02036H L3=0.122H L4=0.195H

C1=0.4μF C2=0.6μF C3=0.4μF C4=1.0μF C5=0.5μF

Figure 3.10: Minimum system configuration

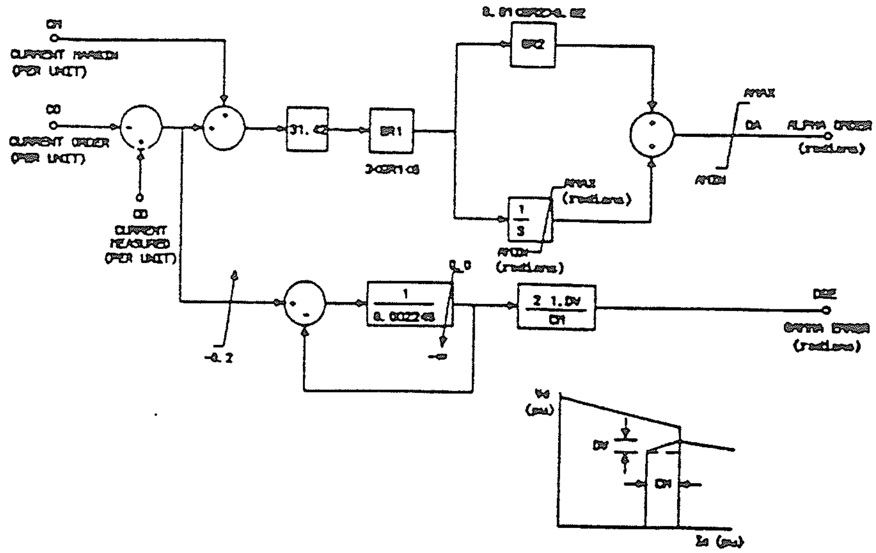


Figure 3.11: Generic pole controller

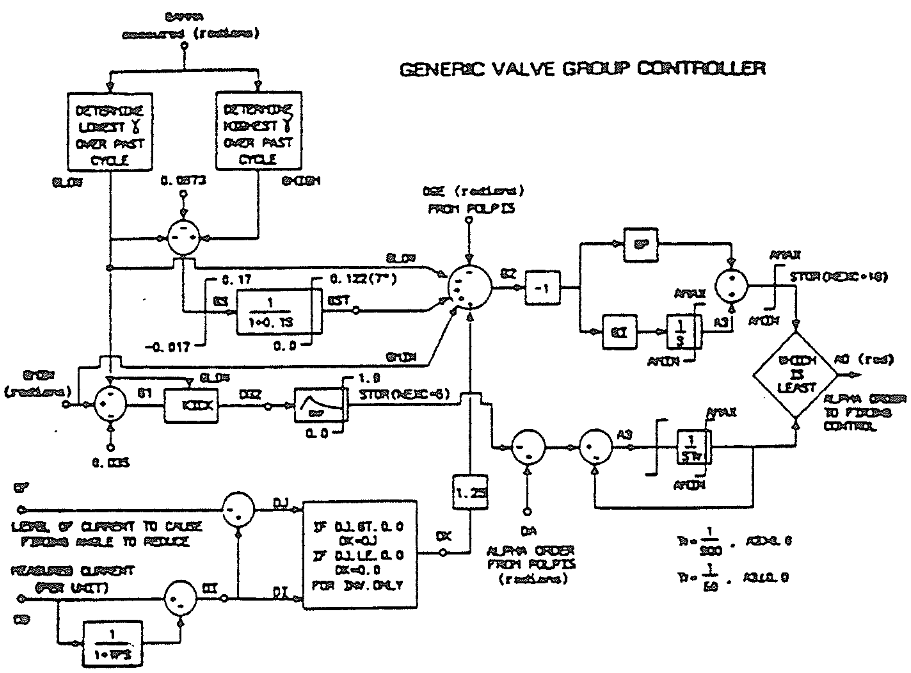


Figure 3.12: Generic valve group controller

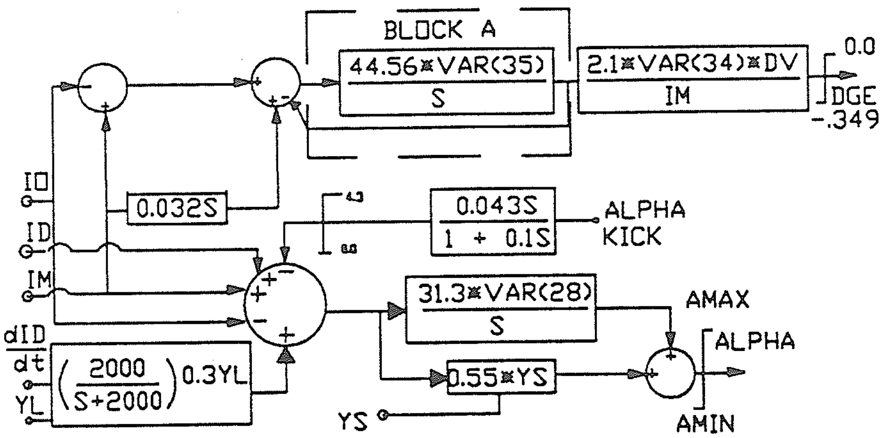


Figure 3.13: Actual pole controller

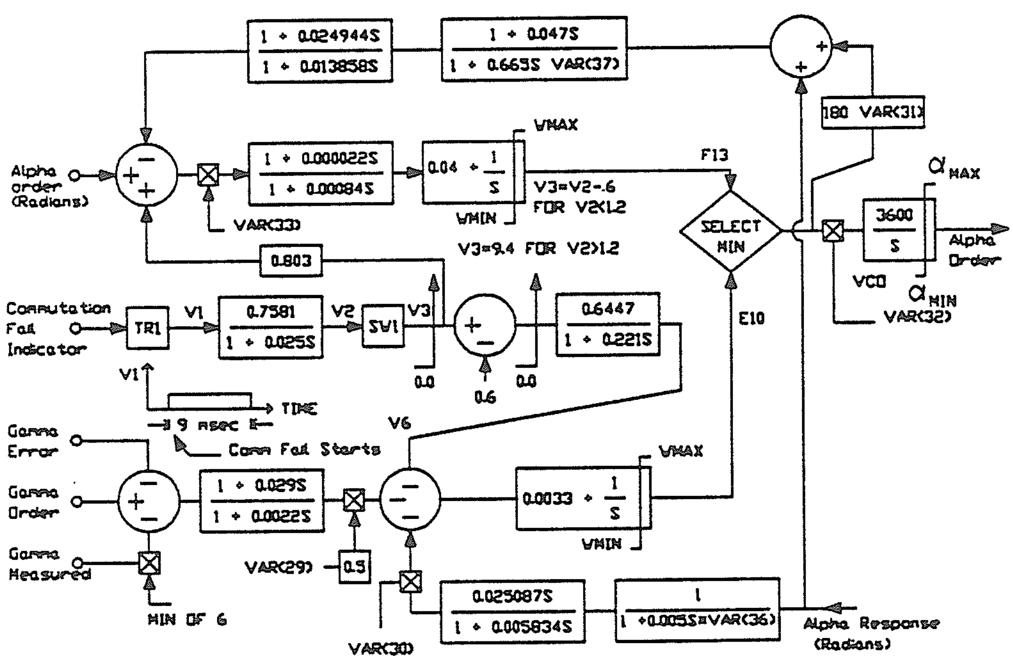


Figure 3.14: Actual valve group controller(bipole1)

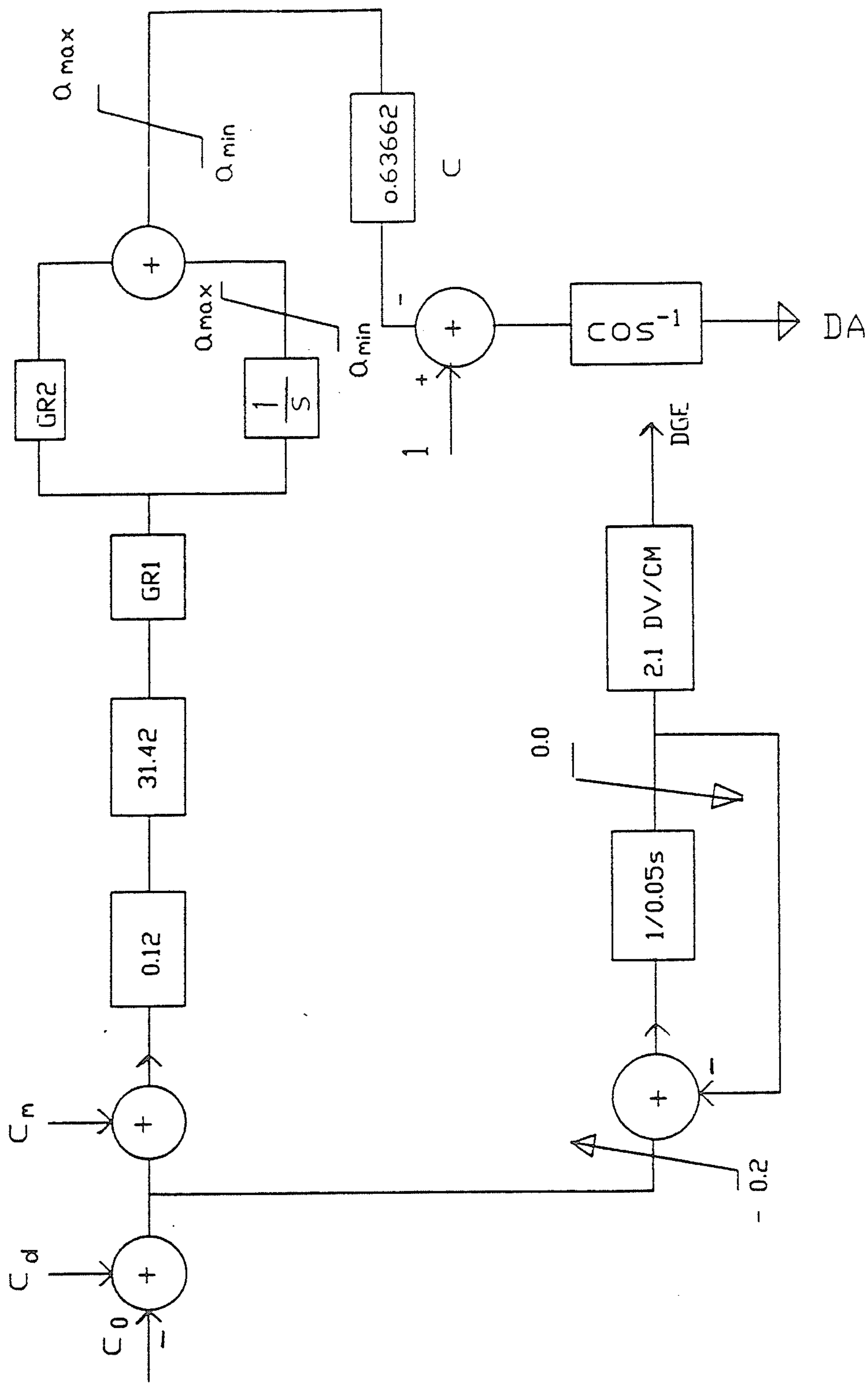


Figure 3.15: Actual pole controller(bipole2)

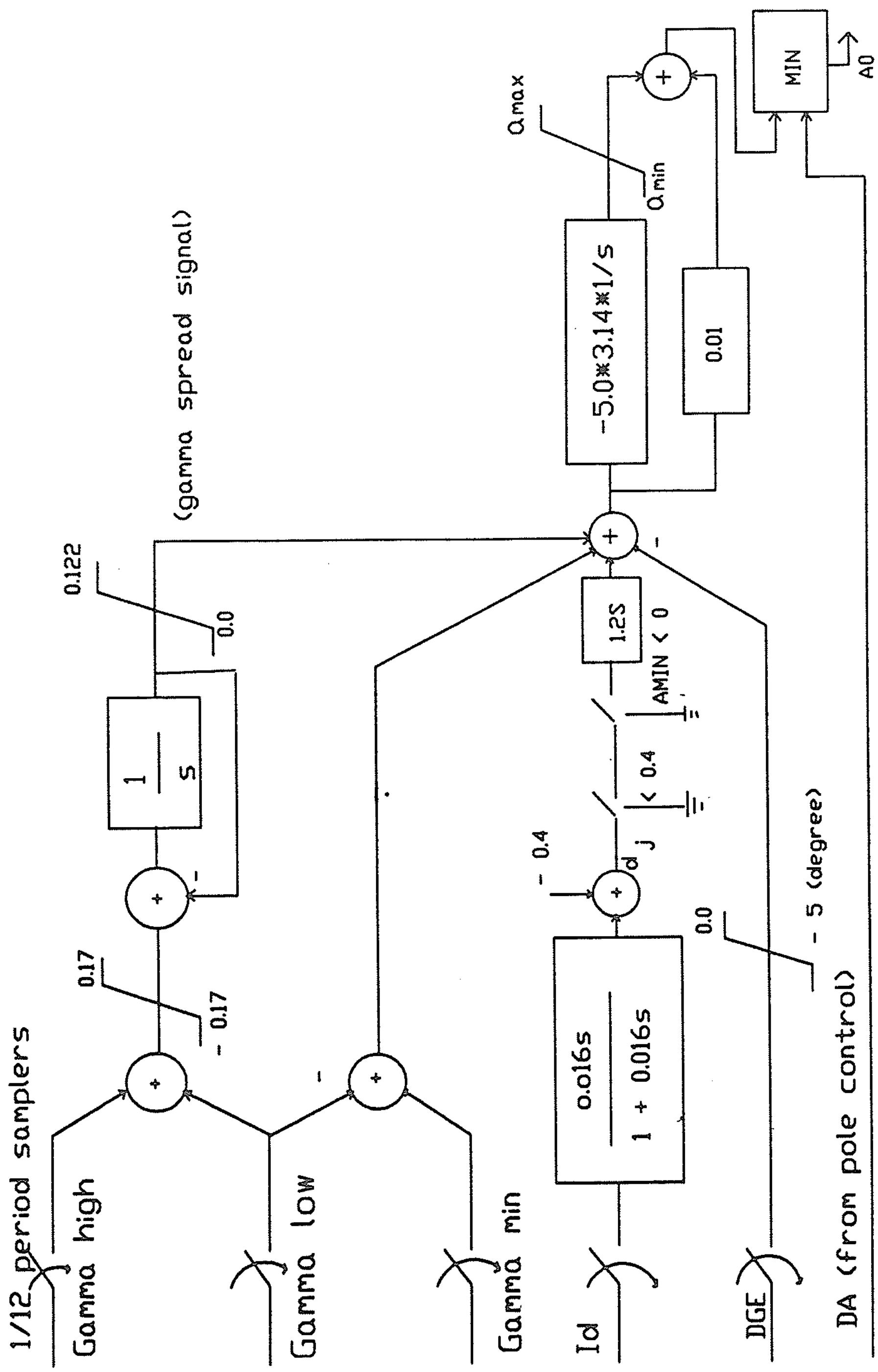


Figure 3.16: Actual valve group controller (bipole 2)

example in Fig. 3.11, a proportional-integral (PI) controller adjusts the order in response to the difference between measured and ordered current. A second path with the signal DGE at its output is used to change the extinction angle (γ) reference in the subsequent valve group controller in order to obtain the chamfered *current error control* characteristic.

A first attempt at modelling can be made by trying to fit the real controls with the generic block diagram. This usually leads to an improper representation, because there may be extra blocks and other signals in the real control systems, or there may be switches that change from one set of controls to another.

For example, Fig. 3.13 shows a section of the actual control block diagram in which there are inputs proportional to the rate of dc current change. As the "Current Error Control" loop (dotted block A of figure 3.13) is critical in the study of these oscillations, it is important to model this loop accurately. Note that some of the control-blocks, such as the derivative block, 0.032s*IM, etc. are absent from the generic diagram of figure 3.11. Similar details are missing in figure 3.12, and are included in figure 3.14. Considerable effort was spent with control diagrams even at the electronic circuit level in order to obtain a proper block diagram of the controls. Also note the bipole2 pole and valve group control's actual control diagram are shown in figure 3.15 and 3.16, and these controllers differ considerably from the generic controllers. Special efforts had to be made to ensure that all control circuit settings from the field were included. This is quite a drawn out process, since a number of control engineers have to be consulted.

Figures 3.17 and 3.18 show the simulation results for the dc current of inverter 1 (Bipole 1) with the use of generic and detailed models respectively. As can be observed, the 6 Hz oscillations are evident in the detailed simulation. Appendix C contains detailed simulation results for this case ie. four different inverter 1 and inverter 2 tap changer settings. In this simulation, the inverters are each conducting approximately 1800A of current. The transformer taps have been adjusted to give the secondary voltage of the inverter 1 transformer a value of 4% above that of inverter 2, ensuring the operation of inverter 1 in current error (CE) control and that of inverter 2 in constant extinction angle (CEA) control.

Most control blocks on the Nelson River controls have response times much larger than the EMTDC time-step, which is used in the simulation. The smaller time-step is required for the simulation of the network elements (Converters, Filters, etc). Consequently, many of the controls can be simulated with a larger time step than the rest of the program (typically 1/12th of a cycle or so). This fact could be used to save computer time. It is important to select the *minimum system* for study by leaving out unnecessary details, however it is not essential to use a *minimum control system,* because the control simulation uses relatively less computer time.

3.5 Study of the Oscillations

Fig. 3.19 shows the result of a computer simulation, carried out on the system for which the site recorder plots are given in Fig. 3.6, 3.7, 3.8 and 3.9. As can be observed, the oscillations on poles 2 and 4 (of Bipole 1 and 2 respectively) are mutually opposite in phase, as they

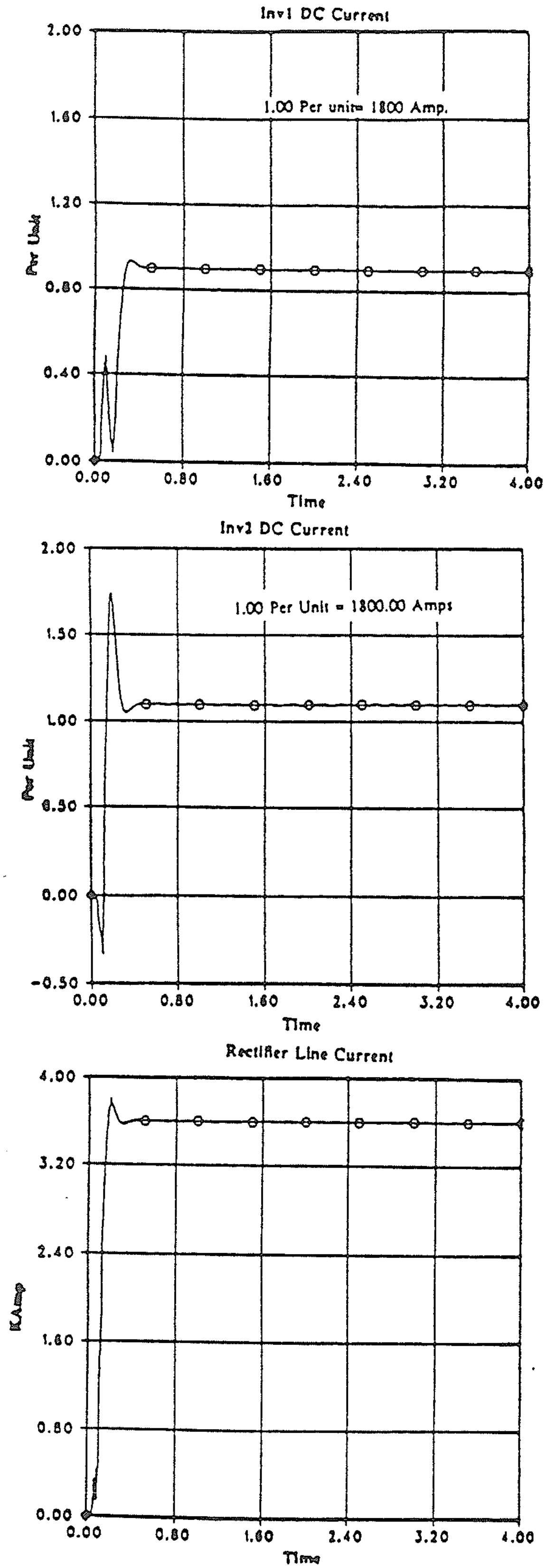


Figure 3.17: Simulation results obtained with generic controller

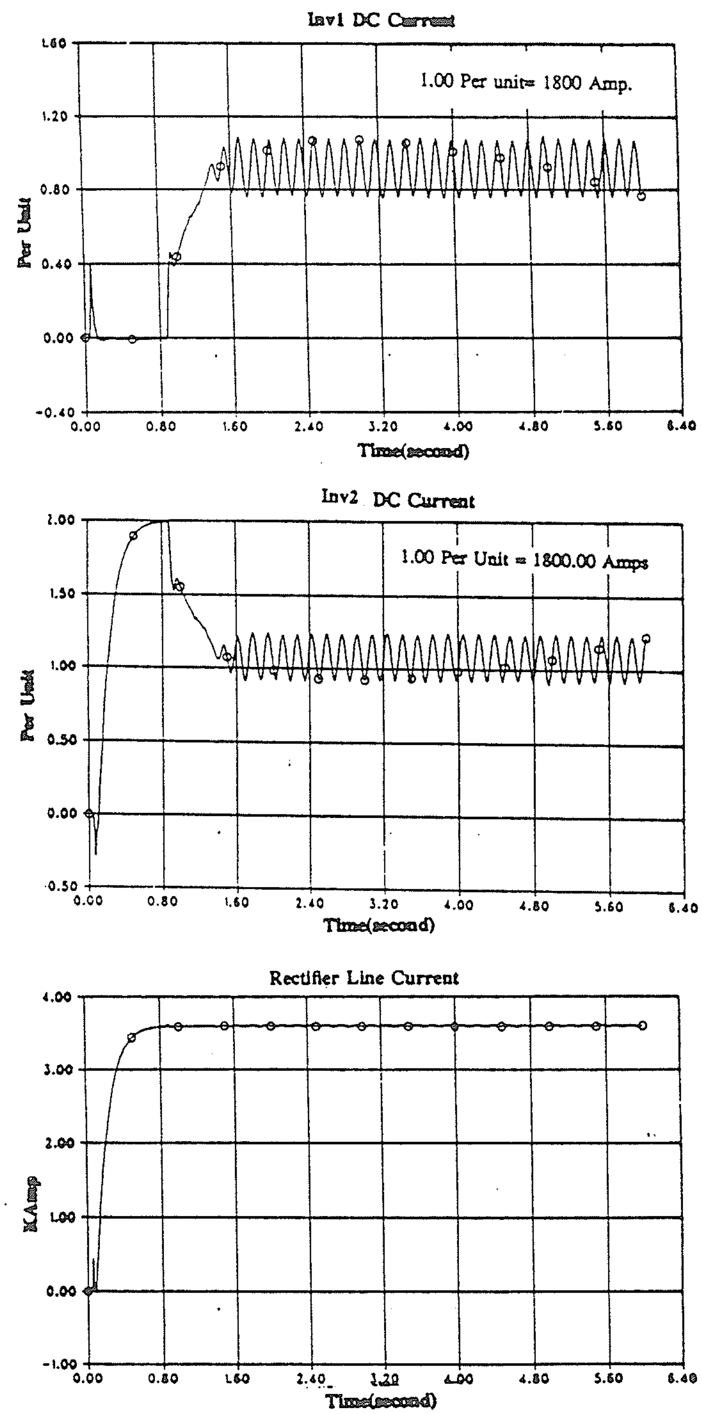


Figure 3.18: Simulation results obtained with actual controller

must be, because the dc line current put out by the rectifier is essentially oscillation free. In our case, the simulated dc rectifier current does have a very small amount of oscillation, and this shows some lack of exact agreement between field and simulated results. The oscillations in the converter's extinction angle were also quite clearly visible. (This trace is not shown in here.) The magnitude of the oscillations are somewhat more in the simulation, but the frequency is quite accurate. It is difficult to get exact agreement on the magnitude of the oscillations, because the magnitude is only limited by inherent non-linearities in the system and controls, which are not easy to estimate and model. We have modelled these with the best information that was available. Table A and Appendix A summarises these simulation results.

Similar simulations were carried out for different system conditions (a smoothing reactor out of service, different loading and tap changer ratios), and yielded acceptable comparisons between field test results and simulation. Table C and Appendix C summarises these simulation results. It was thought that the di/dt signal from the dc current to the pole controller (Fig. 3.13) would play an important role in limiting these oscillations in the current , because derivative control has stabilizing effect on feedback controls. Several simulations with different di/dt gains were attempted, but had marginal effect on the oscillations. It was then observed that there was a particular K/(1+sT) type delay block (see dotted block A in figure 3.13), in the controls, in series with the DGE signal. Decreasing the time constant T from 22ms to 3 ms cured the oscillations in the simulation, as can be evidenced from Fig. 3.20, which is a resimulation of the case shown in Fig. 3.18, but with the control modification introduced. A capacitor in the Bipole 1 controls was replaced to give the real system the same time constant as in the simulation. This resolved the oscillation problem on the real system. Table B and Appendix B summarises these simulation results.

If figure 3.13 is drawn without the di/dt signal and the "[0.032s]" block, (which showed little impact on the oscillations), its structure is very similar to the generic block in figure 3.11. Thus in retrospect, the oscillations could have been demonstrated using the generic pole controller model. However, the pole controller output signals (ALPHA ORDER and DGE) are inputs to the valve group controller, the structure of which differs markedly from the generic block (see for example the feedback loop from the Select Min Block to the Alpha Order summing junction, the Alpha Response signal, etc.). Thus the two controller cascade is very different from that obtained by cascading the two generic controller blocks and hence the oscillations could not be simulated by using only the generic models. Presumably, we could have modeled the valve group controller leaving the generic model for the pole controller, but there was no apriori way of knowing that the di/dt signal would not be important.

The oscillations in the field traces of figure 3.6, 3.7, 3.8 and 3.9 were initiated by a tap changer ratio-change from a configuration of stable operation. Our aim here is to simulate the oscillations and then find ways of eliminating them, and so the traces of figure 3.19 are obtained with the system started up with the tap changer ratios already set. Hence, the dynamics of the growth of the oscillations that is seen in figure 3.6, 3.7, 3.8, 3.9 are not the same as seen in figure 3.19. Also note, bipole2 valve group controller and pole controller diagrams are necessarily different from the generic model, and this difference considerably influence the limit cycle oscillations observed in the parallel multiterminal case.

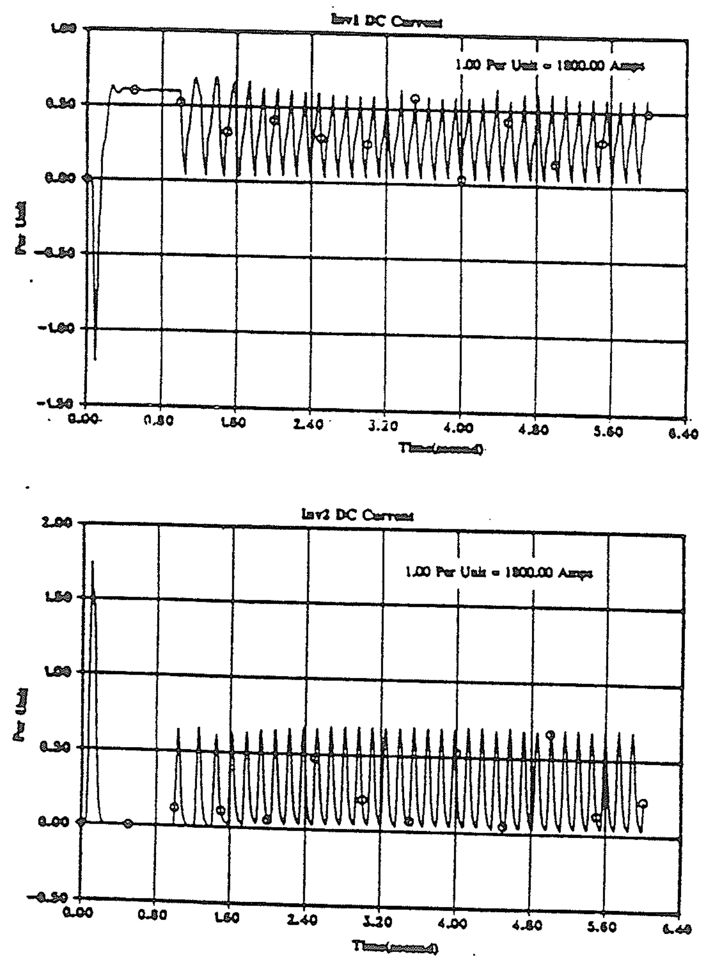


Figure 3.19: Simulation results obtained with current levels as in the field tests

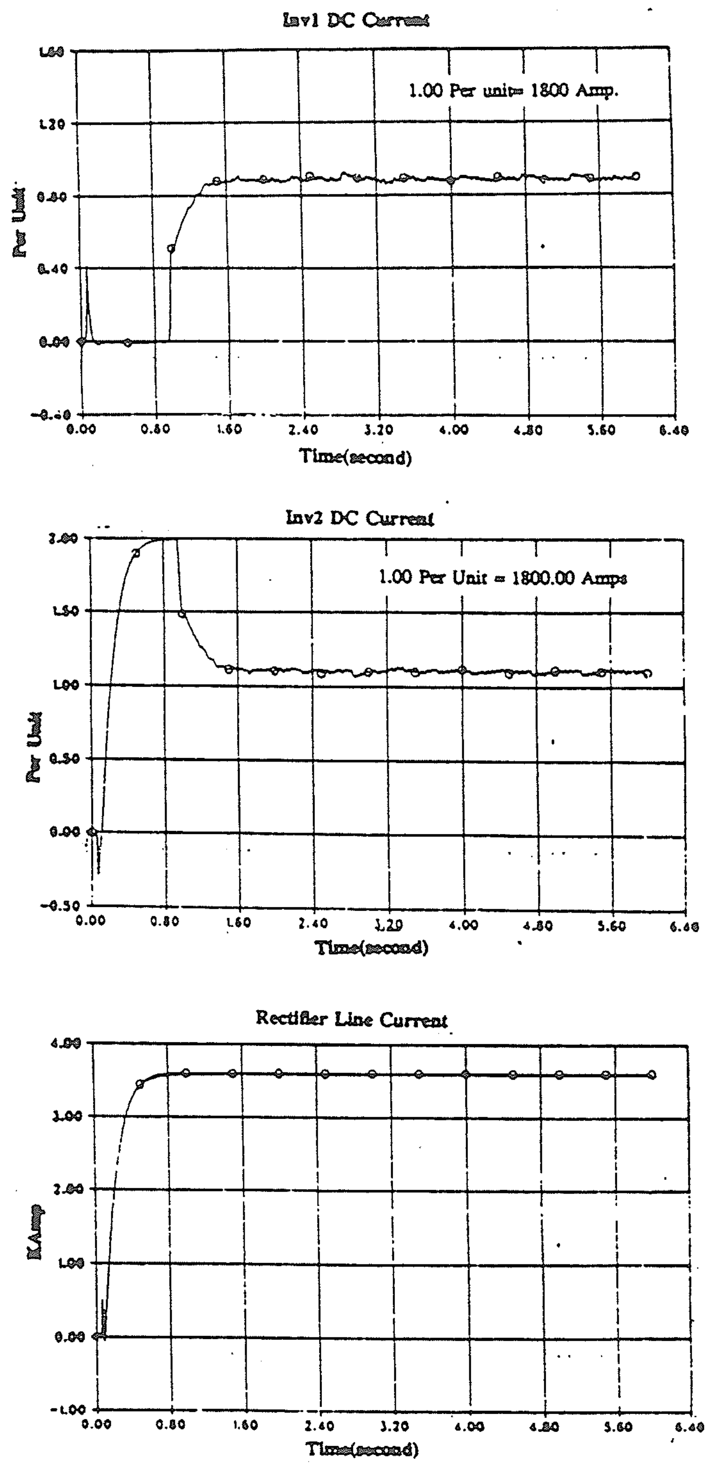


Figure 3.20: Simulation results showing elimination of oscillation with control change

3.6 Simulation Results

In this section, various simulation results are tabulated for easy reference. Three cases of simulation results are tabulated here and they are:

1. Simulation of the inter-bipolar oscillations. This is essentially an attempt to simulate the inter-bipolar oscillations, as observed in figure 3.6 , 3.7, 3.8 and 3.9.

2. Simulation of the inter-bipolar oscillations. This is essentially an effort to stabilize the system so that 6Hz oscillations is removed from multiterminal operation.

3. Simulation of the parallel multiterminal case, when inverter 1 smoothing reactor was out of service. This is essentially an effort to demonstrate that when inverter 1 smoothing reactor was out of service, 8Hz inter-bipolar oscillations observed on the Nelson River Multiterminal system, could be digitally simulated with the detailed control model.

Since the HVDC controller and system has an enormous number of nonlinear parameters, and each of these parameters contains some amount of tolerances , such as passive component values, drift of the operational amplifier comprising the HVDC controller, the 6Hz oscillation case was simulated a number of times with changes to various parameters. Table A records the results of such simulation study. Since parallel multiterminal HVDC simulation uses an enormous number of parameters, the reader is best advised to consult the appendices, for circuit diagrams of bipole1 and bipole2 controller, Dsout and Dsdyn listings, PGB and VAR listings and bipole1 and bipole2 control manuals for detailed understanding of the operation of these controllers. Each of the simulation run included in the appendix has corresponding data file, from which the reader could easily decipher the VAR values for the particular run.

Table A corresponds to the case where we study effect of various parameters on the inter-bipolar oscillation frequency and amplitude. The complete set of graphs corresponding to the four inverter 1 and inverter 2 tap settings are included in Appendix C.

Table B corresponds to the case where we study the effect of various controller parameters to stabilize the inter-bipolar 6Hz limit cycle oscillations. Appendix D contains the simulation results when the Capacitor to decrease the time constant of the Delta Gamma Error (DGE) loop from 22ms to 3ms. Note that the system also could be made stable with reduced gain of the DGE. However, this approach was not taken for the following considerations

1. Since DGE loop has no integrator, reducing the DGE loop gain would increase the steady state error, which is generally considered not applicable.

2. If steady state gain is modified, generally more exhaustive and more detailed simulation runs will be required, since the resulting system with modified DGE loop gain could have less phase and gain margin compared to the original controller.

Table C corresponds to the case when inverter 1 smoothing reactor was out of service. As experienced in the field, this case shows inter-bipolar oscillations of 8Hz among the multiterminal inverter. As before, the table C records various results, when the parameters were varied as mentioned in the table. Appendix E contains the details of one such simulation run. The interested reader is advised to refer to Data, Dsdyn and Dsout files (required for the EMTDC input [10] and the controller diagram for details.

TABLE A

No	INV1 TAP	INV2 TAP	FREQ	AMPL	REMARKS
1	1.00	1.05	0Hz	.5% P-P jitter of I_d	Stable Case Snap run of 6-12 sec.
2	1.00	1.15	0Hz	.5% P-P jitter of I_d	Stable Case
3	1.15	1.00	0Hz	.5% P-P jitter of I_d	Stable Case Snap run from 6-12 sec.
4	1.04	1.00	6.2Hz	29% P-P swing of I_d	Unstable Case As observed in the field

Note for Table B Inverter 1 tap is set at 1.04 pu and Inverter 2 tap is set at 1.00 pu.

TABLE B

No	DGE GAIN	DGE TIME CONSTANT	FREQ	AMPL	REMARKS
1	1.00	2.00	5Hz	42% P-P swing of I_d	BP2 Filters are absent
2	.80	1/25	0Hz	.3% P-P jitter of I_d	Stable case, BP2 12th harmonic and HP filter are removed.
3	.80	1/15	0Hz	.3% P-P jitter of I_d	Stable case No BP2 filters present
4	1.00	1.00	6.0Hz	40% P-P swing of I_d	Gamma feedback time constant increased by 2.0
5	1.00	1.00	8.125Hz	14% P-P swing of I_d	Gamma feedback time constant increased by 5.0
6	1.00	1.00	7.5Hz	16% P-P swing of I_d	Gamma feedback time constant is decreased by 10.0
7	0.80	1/25	0Hz	.2% P-P jitter of I_d	BP2 Filters are present & $L_1 = .6H$
8	0.80	1/25	0Hz	.2% P-P jitter I_d	BP2 Filters are absent & $L_1 = .5H$
9	.80	1/25	0Hz	.2% P-P jitter of I_d	BP2 filters are present and $L_1 = .5H$
10	1.00	1.00	7.5Hz	37% P-P swing of I_d	VCO gain of VG1C36 increased by 50%, no BP2 fltr.

TABLE C

No	INV1 TAP	INV2 TAP	FREQ	AMPL	REMARKS
1	1.04	1.00	6.Hz	25% P-P swing of I_d	$L_1 = .55H$, Original Case
2	1.04	1.00	7.5Hz	25% P-P swing I_d	$L_1 = 0.0H$, $R = 0.1$ohms, smoothing inductor removed
3	1.04	1.00	7.5Hz	25% P-P swing of I_d	$L_1 = 0.0H$, $R_1 = .1$ ohms, Snap run of no 2, 6-12 sec.
4	1.04	1.00	7.0Hz	25% P-P swing of I_d	Smoothing inductor is replaced by $L_1 = 0.0$, $R_1 = 0.5$ ohms
5	1.04	1.00	7.6Hz	24% P-P swing of I_d	Smoothing inductor is replaced by $L_1 = 0.0$, $R_1 = 1.0$ ohms
6	1.04	1.00	7.6Hz	24% P-P swing of I_d	Snap run of case 5, 6-12 sec.
7	1.00	1.05	5.0Hz	25% P-P swing of I_d	$L_1 = 0.0$, $R_1 = 0.0$ ohms, Smoothing inductor removed.

3.7 Conclusion

This chapter shows that careful modelling of an operating dc system on a digital simulation program can result in an useful facility for studying control modifications of the real system. In particular, the chapter demonstrates one such use, where the proposed control modification, for eliminating the observed low frequency oscillations on paralleled bipoles of the Nelson River transmission system, was investigated.

This thesis describes how the choice of the level of modelling-details was made for the study. The need for the detailed modelling of the controls and the accurate determination of parameters from the field are stressed.

Chapter 4

Analysis by Describing Function

4.1 Introduction

In this chapter, we describe an alternative procedure, The Describing Function[15], as an alternative to digital simulation and how it could be used to study the multiterminal HVDC converter's control phenomena.

However, before describing The Describing Function, a survey is performed of available nonlinear system analysis techniques. The analysis requirement which makes the Describing Function particularly suitable for multiterminal HVDC converter study are discussed. Finally, stability criteria of multiterminal HVDC converters is derived and a procedure is delineated which makes it possible to use digital simulation programs for the evaluation of Describing Function.

The Describing Function is defined as the ratio of the fundamental component of the output of the nonlinear system to the amplitude of the input signal. In general, the Describing Function depends on the input signal amplitude and frequency and is complex, because a phase shift may occur between the input and the fundamental component of the output.

For converter systems, which are multi-variable sampled data control systems, the Describing Function also depends upon the phase of the input signal measured in relation to the firing instants. Since the firing pulses are synchronized to the ac system bus voltage, this means that Describing Function of the HVDC control depends upon the phase of the input signal in relation to the ac bus voltage.

If the input to a nonlinear device is a sinusoidal signal, the Describing Function method assumes that the output is a periodic signal having the same fundamental frequency as the input. Therefore, the analysis is concerned only with the fundamental component of the output waveform, all harmonics, sub-harmonics, and any dc component being neglected.

The assumption of a sinusoidal signal applied to the input of the nonlinearity is based on the fact that the amplitude of all waveforms and sub-harmonics of the input frequency are generally much smaller than the amplitude of the fundamental. Furthermore, the low-pass characteristics of the linear element further attenuates the amplitude of all the harmonics of the input frequency. The Describing Function in general, assumes the existence of only one nonlinear element in the feedback loop control system, which is not time varying. If the system contains more than one nonlinearity, they must be either lumped together or treated specially to evaluate an over all Describing Function.

It should be explicitly understood that only theoretical procedure of how the Describing Function techniques could be applied to multiterminal HVDC link's stability analysis is developed in this chapter, and no experimental results have yet been obtained by the author. This chapter has two main purposes in the Multi-terminal HVDC Link's stability analysis.

1. It shows that the Describing Function method of stability analysis provides an alternative means of understanding of the system dynamics; the result of which could be applied to avoid *blind trials* with the off-line digital simulator. In short, the Describing Function provides a quantitative measure of the sensitivity of the system to certain controller variables.

2. The Describing Function is known to provide complete solution to every possible mode of limit cycle oscillations that the system could exhibit. This is extremely valuable since with digital simulation, an user is never sure, whether he has tried enough simulations to demonstrate all the system dynamics.

4.2 Analytical Methods of Analysis

A number of possible ways of studying nonlinear systems may be cited. All of these techniques are important, since different systems may be most amenable to analysis by different methods. Also, it was noted earlier that nonlinear system study must be quite specific since generalization of performance characteristics seems impossible. It may be expected then , that different analysis techniques will be best suitable to the study of different performance characteristics. In effect, different techniques can be used to answer different questions about system performances.

Often the only applicable methods to solve large nonlinear systems are analog simulation or detailed digital simulation. These typically take considerable resources in hardware or time and often do not provide an insight into the behaviour of the system. Digital methods in particular are inefficient when it comes to determining periodic modes and stability boundaries, because the simulations have to be repeated often to achieve this. Analytical methods on the other hand are often more efficient but less accurate because of simplifing assumptions. The previous sections of the thesis dealt with an application of the detailed digital simulation technique. Analytical methods, in general can be divided into exact and approximate methods. The exact methods may be divided into those which attempt to solve nonlinear differential equations and those which provide answers for the important question of stability. Closed form solutions can be found for some nonlinear differential equations but it is rare that a control system problem fits one of these situations. Indeed the majority of the known solutions are restricted to homogeneous equations of the first or second order. A large number of methods exist which express the solution of differential equations in some form of series expansion. The problems of choosing the series form and obtaining satisfactory convergence are such that they have found little use in other than nonlinear systems where the solution to the linear system provides the first term in the series. Thus, although these mathematical methods may occasionally find use in analysis they are of little use, whatsoever in design.

A central question in the design of any nonlinear system is that of stability. Will the system be stable for all forms of input to which it may be subjected?. The work of Lyapunov and more recently of Popov can provide answers to this question without solving the nonlinear differential equation. The Popov method avoids the major difficulty that of Lyapunov, the choice of a positive definite scaler function of the state variables with certain required properties, and is therefore much easier to apply. In addition, the Popov criteria is formatted in the frequency domain which makes for easier comparison with Describing Function methods and also allows use of measured frequency response data. The major disadvantage of these exact methods is that since they provide sufficient and not necessary conditions for stability, they often provide overly conservative estimates for the system stability domain. Also, their application is restricted almost entirely to systems with only one nonlinear characteristic and external input. On the other hand, both methods may be of some assistance in design. It should be noted that all these techniques are useful for design and analysis of the HVDC converter control system. However, The greatest usefulness of each of these techniques depends on the type of nonlinear system study.

4.2.1 Closed Form Solution

There are a number of nonlinear differential equations, mostly of second order, for which exact solutions have been found or for which certain properties of the solution have been tabulated. These constitute a very small number of special cases, and it is rare indeed when a control system arising out of the practical physical situation can be made to conform to one of these second order nonlinear differential equations. The well known Poincarre's equation is one such a candidate, whose closed form solution is known and widely studied in nonlinear control system.

4.2.2 Phase Plane Method

The dynamic properties of system can be described in terms of the differential equations of the state, and an attempt made to solve from the trajectories of the system in the state space. But this is just another way to solve nonlinear differential equations, and it is rarely possible to effect the solution. For the special cases of first and second order systems, however, this approach is useful because the two dimensions available on a flat piece of paper are adequate to display the state of these systems. This graphical technique can be used to solve for the state, or phase trajectories. This allows the response to be calculated for any set of initial conditions and for certain simple input functions. More important, however, is the fact that certain properties of the trajectories, such as their slopes, can be displayed over the whole phase plane. This information helps to alleviate concern over whether enough specific trajectories have been calculated to exhibit all interesting response characteristics. Thus when such phase trajectories can be determined and their characteristics portrayed over the whole phase plane, for certain inputs, one has a most valuable method of attack on the problem. However this can rearly be achieved for systems of greater than second order.

4.2.3 Lyapunov's Direct Method

One of the most important properties of a system, stability, can in principle be evaluated without calculating the detailed responses of the system from given initial conditions with given inputs. All that is necessary is an indication of whether the state trajectories in the vicinity of an equilibrium point tend to move generally toward or away from the point. This concept has most evident application to systems operating without command inputs; certain simple forms of input can also be considered in some cases. An analytic procedure for ignoring the detailed characteristics of the trajectories themselves, and just observing whether or not they tend in a generalized sense toward an equilibrium point, is given by the direct method of Lyapunov.

Lyapunov's method of stability analysis is theoretically possible, but the state variable formulation for the entire system under study is a difficult problem. Moreover there is no well laid out rules for formulating the Lyapunov function for the discrete multirate sampled data control system involving nonlinearities. Lyapunov's direct method of stability although analytically elegant, has little practical applicability at this point.

A positive definite scalar function of the state variables which has certain required properties is defined. It is referred to as a Lyapunov function; We shall denote it as V(x), where x is the vector of state variables. The time rate of change of this function, $V\cdot(x)$, is calculated for motion of x along the system state trajectories. The sign of this derivative function in each of the state space determines whether the state trajectories in that region tend generally toward or away from the origin of the space which is taken at an equilibrium point. Stability or instability of the system can be demonstrated by showing connected regions, including and surrounding the equilibrium point in which $V\cdot$ has consistingly a negative or positive sign.

Failure of any number of choices for the form of the Lyapunov function to demonstrate stability or instability conclusively indicates nothing regarding system properties; it just means that the function tried did not fit properly the characteristics of the system. Only for linear systems we do have well defined procedures for choosing functions which give useful indications of stability. For nonlinear systems, one can try different functional forms, but the search for a good one often goes unrewarded. To quote Popov, who has worked extensively with this method, "the study of stability by means of Lyapunov theorems is in principle universal, but in practice limited."[15] It is even possible to construct V(x) functions whose time derivatives would indicate bounds on a system limit cycle. The concept is very appealing, but its implementation has so far failed to produce usefully tight quantitative bounds.

4.2.4 Series Expansion Solution

A whole family of techniques exist which develop the solutions of nonlinear differential equations or express the dynamic properties of nonlinear system in various forms. These expansion may be a series of nonlinear system operations, a power series in some small system parameter, a power series in the running variable–time in the case of dynamic systems– or some other form. The central question related to these expansion is the speed with which the series converge. One can often solve nonlinear differential equations by simply assuming a series form for the solution, such as a power series in the running variable, and solving for the coefficients in the series which cause the solution to obey the differential equation. But the solution form chosen in this way is completely arbitrary, and one has no reason to expect that it will fit the actual solution efficiently. For example, suppose the system actually has a solution of the form Y(t)=Asin(wt) and the assumed solution is of the form Ya(t)=a+bt+ct**2

This will not generate the solution for an interval of time even with the period of the oscillation with a reasonable of number of terms in the series. More rapidly convergent expressions can be made if one can solve for the approximate response of the system and develop the solution in a series of approximations which fit the solution efficiently. If such a solution to a nonlinear system problem is to be achieved, the leading term in the expansion must be solution to a simpler problem which we are able to solve, and each successive term must be derivable from this in some tractable manner. If we assume that the only problem we are readily able to solve are linear problems, we must expect that the leading term in most useful series solutions will be the solution of a linear problem and subsequent terms in the expansion will attempt to account for nonlinear characteristics of the system. Such expansion can then be expected to converge rapidly only if the system is slightly nonlinear, that is the system properties are describable to a good approximation as properties of linear system. But this is not true of some of the simplest and most common place of nonlinear systems, such as a relay-controlled servo. Thus this method, although they will continue to hold important place in nonlinear system theory, are almost certain to be restricted in applicability.

4.2.5 Linearization

The problem of studying a nonlinear system can be avoided altogether by replacing each nonlinear element by an approximately linear system. This allows one to say a great deal about the performance of the approximating system, but the relation of the performance of the actual system depends on the validity of the linearization approximations.

Linearization of nonlinear operations can be justified only for small departures of the variable from the nominal operating values. Any response which causes the system to go beyond this approximating zone, cannot be described using this technique, unless the system is linearized about the new operating point. In addition, some common place nonlinearities, among other the two-level switch, have a discontinuity at the point which should be chosen as the operating point. Linearization in the ordinary sense is not possible in these cases.

4.2.6 Quasi-Linearization

If the small signal constraint of true linearization is to be relieved, but the advantages of a linear approximation retained, one must determine the operation performed by the nonlinear element on an input signal of finite size and approximate this in some way by a linear relation. This procedure results in different linear approximations for the same nonlinearity when driven by inputs of different forms, or even when driven by inputs of the same form but of different magnitude. The approximation of a nonlinear operation by a linear one which depends on some properties of the input is called quasi-linearization. It is a kind of linearization since it results in a linear description of the system, but it is not true linearization since the characteristics of the linear approximation change with certain properties of the signals circulating through the system.

Quasi linearization enjoys a very substantial advantage over true linearization in that there is no limit to the range of signal magnitudes which can be accommodated. Moreover, a completely linearized model can exhibit only linear behaviour, where a quasi linearized model exhibits the basic characteristics of nonlinear behaviour dependence of performance on signal amplitude. On the other hand, a quasi-linearized model is more difficult to apply. A linearized model depends only on the system and the choice of nominal operating point. A quasi-linearized model depends on the system and certain properties of the signals circulating in that system. This gives rise to the inevitable requirement for simultaneous solution of two problems: (1) The quasi-linearized model is used to solve for the signals in the system, and (2): certain properties of these signals are used to define the quasi-linearized model. In spite of these difficulties , quasi-linearization stands as a most valuable tool in nonlinear-system study. A substantial number of interesting and important characteristics of nonlinear system behaviour can be studied better with this technique than any other.

4.2.7 The Describing Function

With the requirement that the linear part of the system filter the output of the nonlinearity sufficiently, Describing Function theory provides answers to quite general questions about nonlinear system operation. The response of the systems to the whole class of inputs consisting of linear combinations of signal forms, such as bias, sinusoidal and Gaussian Process can be calculated. Even more general system inputs can be handled; the only requirement is that the input to the nonlinearity be of appropriate form.

The Describing Function technique has its limitations as well. The fundamental limitation is that the form of the signal at the input to the nonlinearity must be guessed in advance. For feedback configuration, this guess is usually taken to be one of the limiting signal forms discussed above. A less obvious limitation, which is probably true of every method of nonlinear study, is the fact that the analysis answers only specific questions asked of it. If the designer does not ask about all important aspects of the behaviour of a nonlinear system, Describing Function analysis will not disclose this behaviour to him.

Another difficulty which the user of Describing Function theory must be alert to is the possibility of multiple solutions. Formulation of a problem using Describing Function results in simultaneous set of nonlinear algebraic relations to be solved. More than one solution may exist. These solutions represent different possible modes of response, some of which in some cases may be shown to be unstable.

A final limitation on the use of Describing Function theory is the fact that there is no satisfactory evaluation of the accuracy of the method. Research into this problem has resulted in some intuitively based criteria which are rather crude and some analytically based procedures which are impractical to use.

The best method of nonlinear system study is to combine both the techniques, ie. digital simulation and analytical techniques. Since HVDC converter is a nonlinear discrete time system the only practical method that can be applied is the Describing Function method. The Describing Function technique is approximate but it is the only analytical technique available to study large signal phenomena as was the case with Nelson River HVDC system.

4.3 Consideration Regarding Choice of Analytical Techniques

Figure 4.1 shows the three terminal HVDC link, which was used to study the Nelson River HVDC links stability problem. A couple of important points should be considered before the above system could be analyzed analytically.

The HVDC converter is a discrete, multirate sampled, nonlinear system. Also the pole controller, group controller and Phase Locked Loop (PLL) based valve firing system contains a large amount of nonlinearities. In particular the HVDC converter and three phase PLL modelling, which takes dynamics of the system into account, is a difficult task in itself, but nevertheless such accurate modelling is the essence of success for analytical study.

Lutz and Persson [24] [31] have developed the dynamic model of the HVDC converters over the years, and all of them approximate HVDC converters as the linear element with single sampling clock. In reality six and twelve pulse converters must be modelled with six and twelve sampling clocks or in another words as the multirate sampled data system. Nevertheless one can imagine that such modelling could be unusually complex. At this point of time to the best of my knowledge no linear dynamic model of the six pulse or twelve pulse valve group model exists in literature that uses multirate sampling techniques to model the HVDC converter.

The linearized discrete time model developed so far suffers from the following limitations

1. This model fails to predict limit cycle oscillations synchronized with the ac system voltage especially for the case of limit cycle oscillations at half the firing frequency.

2. This model cannot take into account unbalance or distortion in the ac bus voltage.

3. It can not take into account unbalance in the converter transformer leakage reactance.

4. It can not determine the inherent nonlinear phenomena of the converter.

   Modelling of the voltage controlled oscillator based phase locked loop–which establishes the firing instants of the individual valves in relation to the ac supply waveforms–

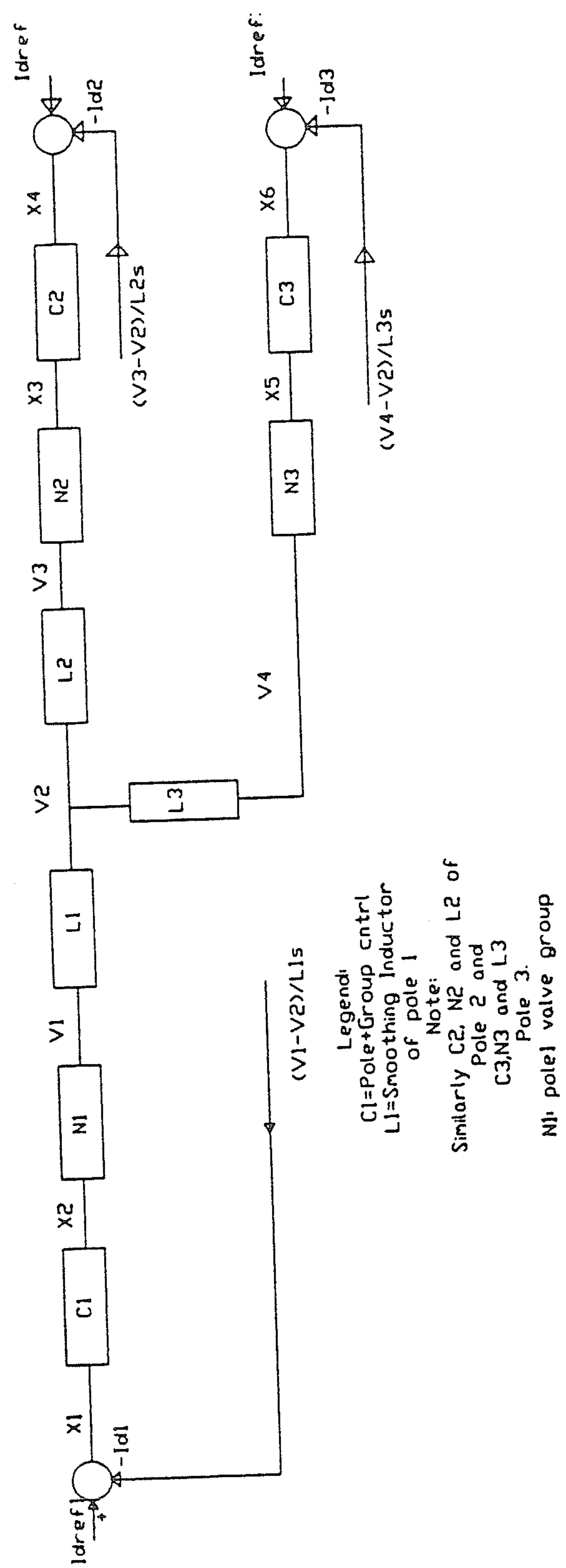


Figure 4.1: Converter functional block diagram

is complex and involves discrete phenomena and accurate modelling of such PLL is required. Present literature proposes models of such PLL which neglects the discrete nature of such PLL altogether and instead approximates the dynamics of such PLL with a first order system with a certain synchronization time constant.

Also note that the three terminal HVDC system shown above has three major control loops which employ both discrete time –such as HVDC converter – and continuous control elements–such as pole and group controller. If we neglect the nonlinearity of the control element for the moment, there is no suitable way of finding the transfer matrix of the system in the Z transform domain, since there are no switches or sampling element at the three inputs of the system. Stated in other way, in the Z domain there is no characteristic matrix equation from which conventional stability analysis and eigenvalue analysis could be performed. In other words, it is not possible to apply the sampled data control system theory to the above problem. Moreover the problem at hand is the study of limit cycle phenomena, which is essentially a nonlinear system manifestation, and linear Z transform theory is not capable of predicting such system behaviour.

Faced with such conflicting analytical inadequacies, I was forced to choose an analytical procedure which should be practical and should retain the nonlinear element of the system under study. It was also agreed to overlook the detailed dynamics of the system such as multirate sampling feature of the HVDC converter and the three phase PLL, the rationale behind such choice was as follows: since limit cycle oscillations of 6hz were being investigated, which is much lower that the multirate sampling frequency of the converter the multirate sampling feature of the converter could be overlooked. As a note of caution, such multirate sampling feature will be important if high frequency instability of the system was being investigated. Also for the 6Hz instability study the PLL could be adequately modelled as first order system with some specified synchronization time constant, since all throughout the instability period the PLL was in synchronization with the ac system. This is so since typical PLL synchronization time is much smaller that the instability oscillation time period.

4.4 Mathematical Expression for Describing Function

In order to derive a mathematical expression for the Describing Function, consider the nonlinear feedback system of figure 4.2. If the input to the nonlinear element is given by

$$X(wt) = X * Sin(wt) \tag{4.1}$$

The steady-state output y can be expressed by the series

$$Y(t) = Y_1 * Sin(wt + \Phi_1) + Y_2 * Sin(2wt + \Phi_2) + ... \tag{4.2}$$

The Describing Function is by definition the ratio of the phasor magnitude of the output component frequency $w$and the phasor representation of the input.

$$N(X,w) = \frac{Y_1(X,w)e^{j\Phi_1(X,w)}}{X} \tag{4.3}$$

The Describing Function depends upon the amplitude and frequency of the input signal. The nonlinear effect is manifested in terms of gain and phase margin varying with the amplitude and frequency of the input signal.

The condition for the existence of a limit cycle in a nonlinear feedback system can be predicted through the Describing Function, assuming that the linear element has a low-power characteristics which effectively filters the harmonics of frequency higher than w. A sustained oscillation of amplitude X and frequency w can exist if the following equations is satisfied.

$$1 + N(X,w)G(jw) = 0 \tag{4.4}$$

This condition can be written as

$$G(jw) = -\frac{1}{N(X,w)} \tag{4.5}$$

or, alternatively

$$N(X,w) = -\frac{1}{G(jw)} \tag{4.6}$$

The Nyquist diagram or the Nichols chart (Gain-phase plot) are most widely used techniques for stability analysis utilizing the Describing Function method. Two separate sets of loci, corresponding to G(jw) and $-\frac{1}{N(X,w)}$ (or, alternatively $-\frac{1}{G(jw)}$ and N(X,w)) are plotted on the same graph for either of the two methods. In general, the sketch of - $-\frac{1}{N(X,w)}$ will be a family of curves for different amplitudes of X and frequency w.

Intersection of the two loci indicates possible solutions of equation 4.4 and provides information as to the magnitude and frequency of sustained oscillations. If no inter section occurs, an oscillation is unlikely. This is illustrated in figure 4.3, which indicates the possibility of a limit cycle oscillation of frequency W_0 and amplitude X_0.

An important question whether the limit cycle is itself stable or unstable. This can be determined by means of a perturbation analysis around the limit cycle.

A generalized method can be established for the gain-phase plot as shown in figure 4.4a. If the two loci are assigned a positive sense so that the linear locus G(jw) is pointing towards increasing frequency and the nonlinear locus $-\frac{1}{N}$ is pointing in the direction of increasing amplitude, then a stable limit occurs when the nonlinear locus appears to an observer, stationed on the linear locus and facing the direction of increasing frequency, to cross from left to right in the direction of increasing amplitude.

If a polar plot is used instead, then the limit cycle is stable when the nonlinear locus crosses the linear locus from right to left in the direction of increasing amplitude, as illustrated in the figure 4.4b.

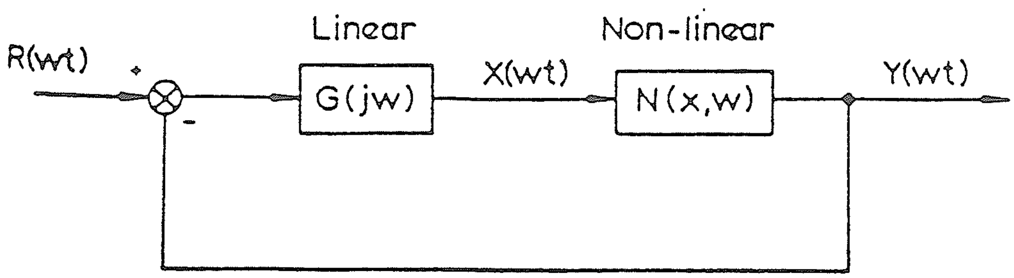


Figure 4.2: General nonlinear feedback system.

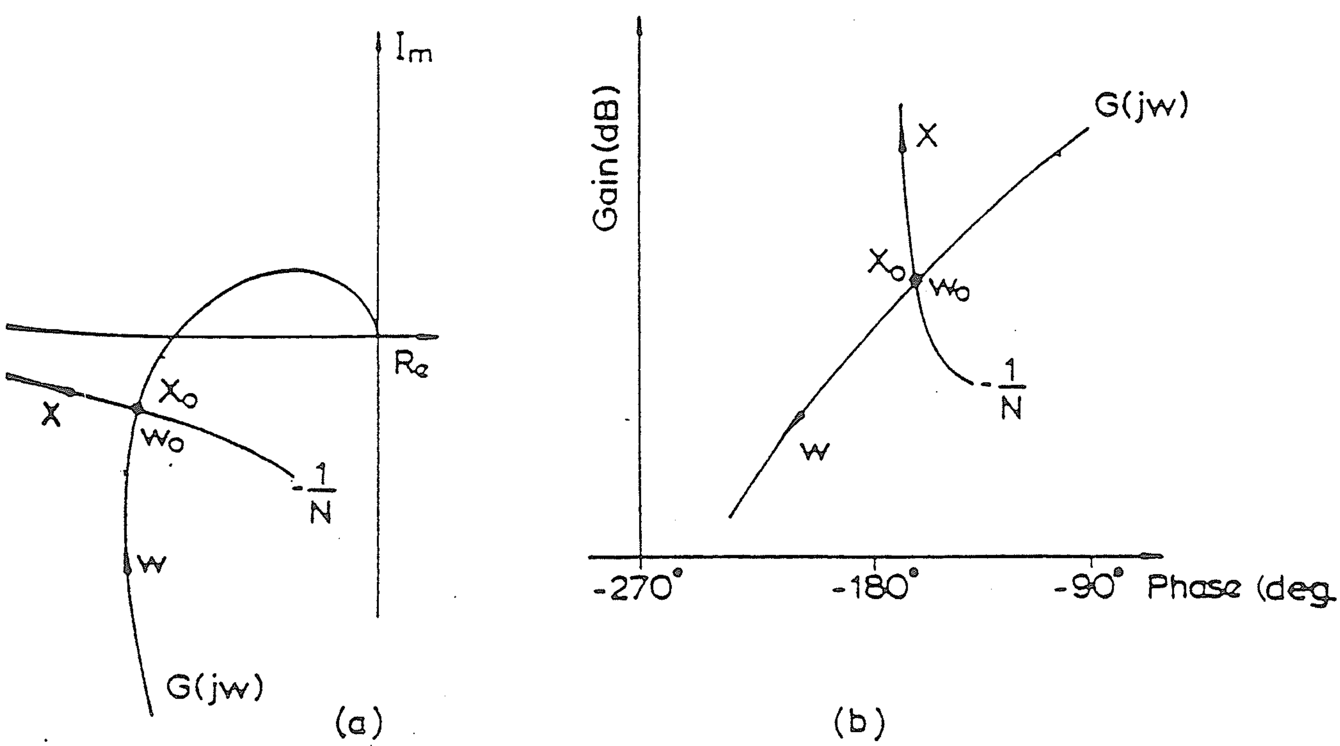


Figure 4.3: Limit cycle with frequency W_0 and amplitude X_0 (a) Polar plot (Nyquist) (b) Gain-phase plot (Nichols)

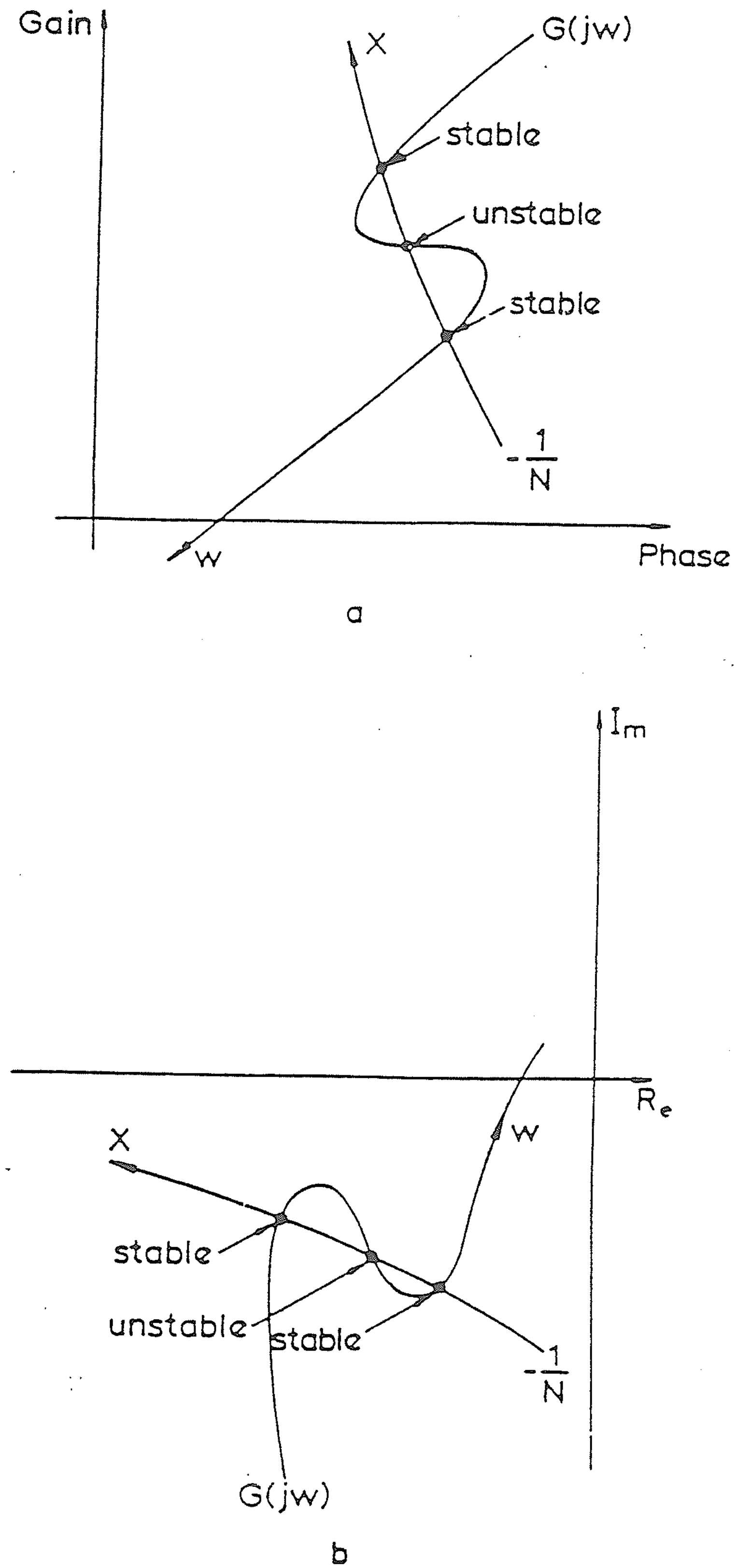


Figure 4.4: Stability and instability of limit cycles (a) Gain-phase plot (b) Polar plot

4.5 Describing Function for Sampled Data System

A nonlinear sampled data system is represented in figure 4.5 [15]. For such a system it should be borne in mind that frequencies other than the fundamental are generated by both the nonlinearity and the sampler.

The output of an ideal sampled system, the input to which is a sinusoidal signal of frequency w, is given by

$$Y^*(jw) = \frac{1}{T_s} \sum_{k=-\infty}^{\infty} Y(j(w + Kw_s)) \quad (4.7)$$

Where w_s is the sampling frequency and T_s is the sampling period ($w_s = 2\pi/T_s$).

Referring to figure 4.5, the frequency components of X(t), Y(t) and $Y^*(t)$ are given by

Signal	Frequency Component
X(t)	$\pm w$
Y(t)	$\pm lw$
$Y^*(t)$	$\pm lw \pm Kw_s$

Where l and k are integers 0,1,2,3. If $\frac{w}{w_s}$ is irrational, ie. if the frequency of x(t) is not locked to the sampling frequency, $Y^*(t)$ is aperiodic. If on the contrary, $\frac{w}{w_s} = \frac{m}{n}$, $Y^*(t)$ is periodic with a period multiple of $\frac{2\pi m}{w}$. A particular case of this occurs when $\frac{w}{w_s} = \frac{1}{n}$, ie. the input frequency is a sub-harmonic of the sampling frequency. $Y^*(t)$ is periodic with a period of $\frac{2\pi}{w}$.

If $\frac{w}{w_s}$ irrational or $\frac{w}{w_s} \neq \frac{m}{n}$ then $Y^*(t)$ may contain frequencies less than w. These are produced by modulation of high frequency harmonics of Y. Since the frequency spectrum Y^* is $lw_s \pm kw_s$. If $\frac{w}{w_s} = \frac{1}{n}$, Y^* contains no frequencies (other than dc) lower than w. One can therefore conclude that the filtering hypothesis upon which the Describing Function method is based is only valid when the input signal is a sub-harmonic of the sampling frequency. This is also the case of greatest practical importance.

Furthermore, the phase relationship between the sampling instants and the input signal affects both the magnitude and phase of the Describing Function. For a given amplitude of the input, and letting the phase vary from zero to 2π radians, a closed curve is obtained. The Describing Function is therefore defined as

$$N(X, w, \Phi) = \frac{Y_1(X, w, \psi)}{X} e^{j(\Phi_1(X,w,\Phi)-\psi)} \quad (4.8)$$

for an input signal

$$X(wt) = Xsin(wt + \psi) \quad (4.9)$$

The condition for existence of a limit cycle can then be written as

$$1 + N(X, w, \phi)G(jw) = 0 \tag{4.10}$$

A feedback system with a controlled converter is in many ways similar to sampled data control system, in particular, when the converter is connected to an infinite bus bar. If the ac bus is finite, the similarity is not so close, however, many features of the Describing Function for sampling systems also apply to power converters.

4.6 The Dual Input Describing Function

The dual input Describing Function is a particular case of the single input Describing Function method [15]. In the dual input Describing Function, the input signal to the nonlinear element is assumed to possess two frequencies, ie.

$$X(t) = X_1 Sin(w_1 t) + X_2 Sin(w_2 t + \psi_2) \tag{4.11}$$

Where ψ_2 is the phase of the signal at frequency w_2 relative to signal reference. The steady-state output Y(t) can be implemented as :

$$Y(t) = \sum_{k=0}^{\infty} Y(k) Sin(w_k t + \Phi_k) \tag{4.12}$$

The dual input Describing Function for frequency w_1 is there fore

$$N_{w_1}(X_1, X_2, w_1, w_2) = \frac{Y_1 e^{j\Phi_1}}{X_1} \tag{4.13}$$

and for frequency w_2

$$N_{w_2}(X_1, X_2, w_1, w_2) = \frac{Y_2}{X_2} e^{j(\Phi_2 - \psi_2)} \tag{4.14}$$

It can be shown that the influence of the signal with frequency w_2 on N_{w_1} and w_1 on N_{w_2} depends on whether the frequencies w_1 and w_2 are related or not. If the ratio $\frac{w_1}{w_2}$ is not a ratio of integers (these frequencies are known as incommensurate) N_{w_1} depends only on the amplitude of both the frequencies and not on the phase ψ_2. If the ratio $\frac{w_1}{w_2}$ is a ratio of integers (these frequencies are thus called commensurate), N_{w_1} and N_{w_2} depends on the amplitude and phase of the input signals.

In the case of control loop with controlled converters, the frequency of the input signals are commensurate and thus only this case is of relevance. For commensurate frequencies, the dual input Describing Function is a closed curve. Figure 4.6 shows an example of such a Describing Function.

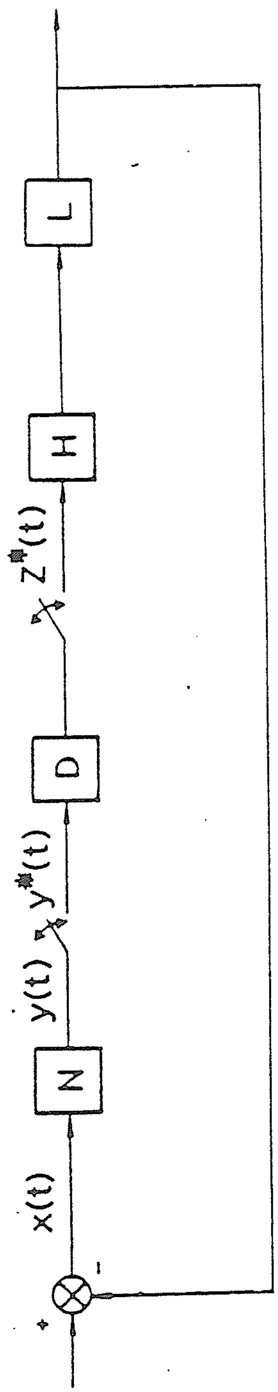


Figure 4.5: Non-linear sampled-data feedback system

For the sampled data systems, the double input Describing Function for input frequencies w_1 and w_2 can be described as

$$N_{w_1}(X_1, X_2, w_1, w_2, \psi_1, \psi_2) = \frac{Y_1(X_1, X_2, w_1, w_2, \Phi_1)}{X_1} e^{j(\Phi_1(X_1, X_2, w_1, w_2, \psi_1, \psi_2) - \psi_1)} \quad (4.15)$$

For an input signal

$$X(t) = X_1 Sin(w_1 t + \psi_1) + X_2 Sin(w_2 t + \psi_2) \quad (4.16)$$

The condition for the existence of a limit cycle of frequencies w_1 and or w_2 can therefore be written as

$$1 + N_{w_1}(X_1, X_2, w_1, w_2, \psi_1, \psi_2) G(jw_1) = 0 \quad (4.17)$$

4.7 Describing Function for HVDC Converter

In this section, we have extended the Describing Function method to include the HVDC converter. HVDC systems invariably operate in a feedback control loop as represented in figure 4.7. The Describing Function refers to the hatched box, which contains the converter (Nonlinear element), the firing systems and the dc system. To evaluate the Describing Function, a signal of amplitude V_m, frequency w and phase ψ is superimposed on the steady-state control voltage V_c. This control voltage is a measure of the firing angle alpha and input to VCO. The dc current i_d will contain a term at frequency w with amplitude I_{dw} and phase Φ_{dw}. The Describing Function for the HVDC converter is therefore developed as

$$N_{I_{dw}}(V_m, w, \psi) = \frac{I_{dw}}{V_m} e^{j(\Phi_{dw} - \psi)} \quad (4.18)$$

Similarly, for the α response loop we have.

$$N_\alpha(V_m, w, \psi) = \frac{\alpha_w}{V_m} e^{j(\Phi_{\alpha w} - \psi)} \quad (4.19)$$

Where α_w is the value of the α response, and has phase value of $\Phi_{\alpha w}$ with respect to firing signal.

Similarly for the γ response loop we have

$$N_\gamma(V_m, w, \psi) = \frac{\gamma_w}{V_m} e^{j(\Phi_{\gamma w} - \psi)} \quad (4.20)$$

Where γ_w is the value of the γ response, and has phase value of $\Phi_{\gamma w}$ with respect to the firing signal. So in essence for the HVDC converters, we have three Describing Functions corresponding to the direct current, α response and the γ response. This complicates the stability analysis, but the procedure to evaluate the limit cycle oscillations essentially remains the same.

For a given frequency and amplitude of the input signal, the Describing Function depends upon its phase. Letting the phase vary from 0 to 350 degrees, a closed curve is obtained.

To evaluate the dual input Describing Function, a signal of the form

$$V_m(t) = V_{m1}Sin(w_1 t + \psi_1) + V_{m2}Sin(w_2 t + \psi_2) \tag{4.21}$$

is superimposed on the steady-state control voltage V_{c0}. The dc current I_d will contain terms at frequency w_1 and w_2. The double input Describing Function for input signal at frequency w_1 is defined as

$$N(V_{m1}, V_{m2}, \psi_1, \psi_2, w_1, w_2) = \frac{I_{dw_1}}{V_{m1}} e^{j(\Phi_{dw_1} - \psi_1)} \tag{4.22}$$

The dual input Describing Function for α response and γ response is similarly defined. The dual input Describing Function for input signal at frequency w_2 is defined similarly. Thus for given frequency w_1 and amplitude V_{m1} of the input signal, the dual input Describing Function depends on the phase ψ_1, the amplitude and frequency of the bias signal V_{m2}, w_2 and on the phase of the bias signal ψ_2. For each phase ψ_1 of the input signal at frequency w_1 the phase of the bias signal is varied from 0 to 360 degrees. An example of the plot of the dual input Describing Function for HVDC system is seen in Figure 4.8. The hatched line corresponds to the Describing Function locus for a signal with frequency w_1 and amplitude V_{m1}. When a bias signal of frequency w_2 and amplitude V_{m2} is introduced, each point of the Describing Function locus develops into a closed curve.

Both the evaluation of the single input Describing Function and dual input Describing Function can be achieved through the off line digital simulation program EMTDC. The phase of the input signal could be increased from 0 to 350 degrees in steps of 10 degrees. If the double input Describing Function is to be computed, for each phase of the input signal at frequency w_1, the phase of the bias signal is varied from 0 to 350 degrees in steps of 10 degrees. Thus for the ordinary Describing Functions 36 steady state solutions of the HVDC system are required, where as for the double input Describing Function 1296 solutions would be required.

However, the computation of the double input Describing Function is only needed in some cases. Generally for the prediction of limit cycle, it is sufficient to plot the double input Describing Function for points of the Describing Function when the gain and or phase margin are quite small. Moreover, the influence of this bias signal is generally small, ie. in most cases it is sufficient to evaluate the single input Describing Function. The use of the dual input Describing Function however could be restricted for a more accurate result. test results.

The distinctive feature of the frequency response of the HVDC converter at the particular frequency is that the output becomes dependent on the phase of the input signal and instead of a single point on the complex plane, as is the case for frequencies unrelated to the firing frequency, a circle is traced. Moreover, due to the nonlinearity of the system, the radius of the circle depends on the magnitude of the input signal. The linearized model does predict a circle only at half the pulsing frequency, a feature of all sampled data control systems.

Unbalance and or distortion in the ac voltage has a definite effect on the magnitude of the circle, which can significantly increase under certain circumstances, indicating that instability is more likely to occur. the same consideration apply to the converter transformer core saturation, which has similar effect on the frequency response of the converter system.

4.8 Determination of the Describing Function with EMTDC

The Describing Function method has been applied to converter stability [12] before. However, obtaining the describing Function is a rather involved procedure. Here, we present an alternative using digital simulation software.

To obtain a Describing Function using EMTDC, it is necessary to modulate the steady state control voltage (proportional to the firing angle α) with a signal of amplitude V_m, frequency w and phase ψ and to measure the dc current harmonic of the same frequency. The Describing Function is given by the expression

$$N(V_m, w, \psi) = \frac{I_d e^{j\Phi_{dw}}}{V_m e^{j\psi}} \tag{4.23}$$

and the same formulation could be extended to the Describing Function measurement of α response and the γ response.

The procedure involves calls for the use of a *digital transfer function analyzer.* The digital transfer function analyzer is used to generate the modulating control voltage V_c and to measure the harmonic of direct current of interest. A schematic diagram of the procedure is shown in figure 4.9. The digital transfer function analyzer could be modelled as a subroutine in the EMTDC.

The digital transfer function analyzer consists of a source, which is used to modulate the control voltage and a Digital Correlator. The digital correlator picks out the sine wave component that possess the same frequency as the one set in the function generator and rejects other harmonics and noise. The in-phase and quadrature components of the waveform to be analyzed are measured relative to sine and cosine reference signals derived directly from the function generator.

In order to lock the output of the function generator to the ac system voltage, one single-phase phase lock loop could be used. And if less rigorous synchronization is satisfactory, Schmitt trigger or a comparator could be used [44].

The Describing Function of a controlled converter is generally obtained for a particular value of steady state control voltage, which corresponds to a nominal firing angle

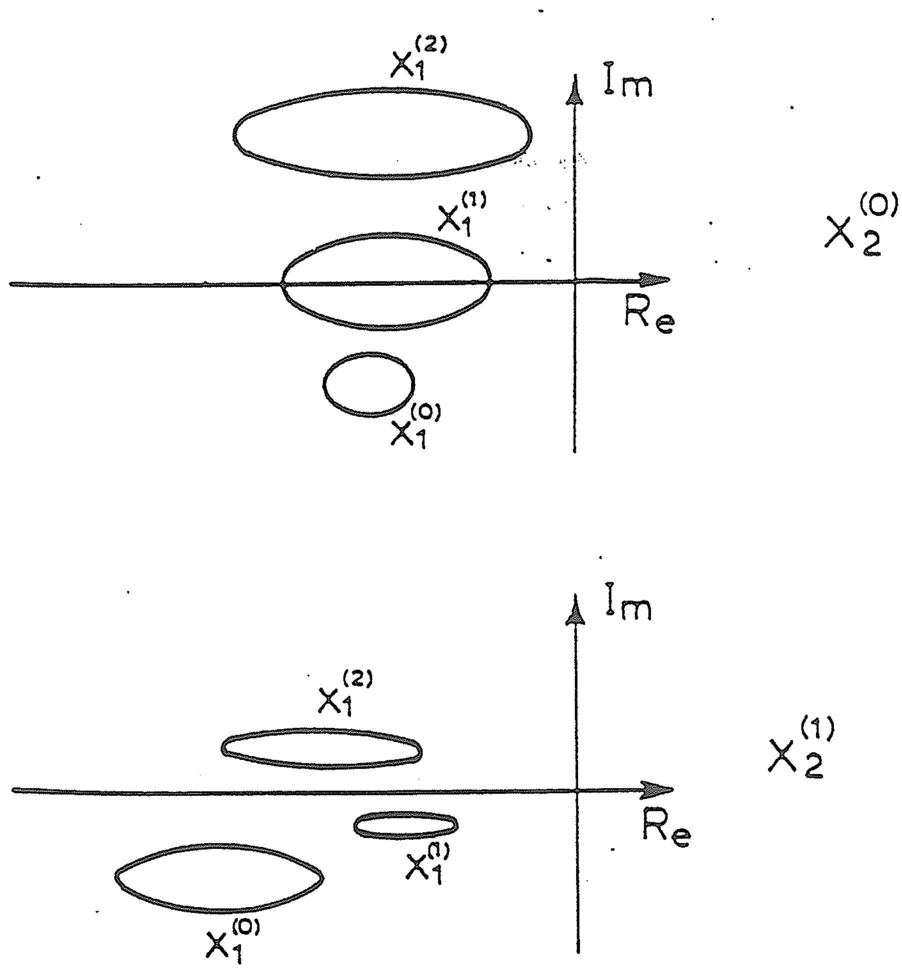


Figure 4.6: Dual-input Describing Function N_{w1} for amplitudes of bias signal equal to X_2^0 and X_2^1.

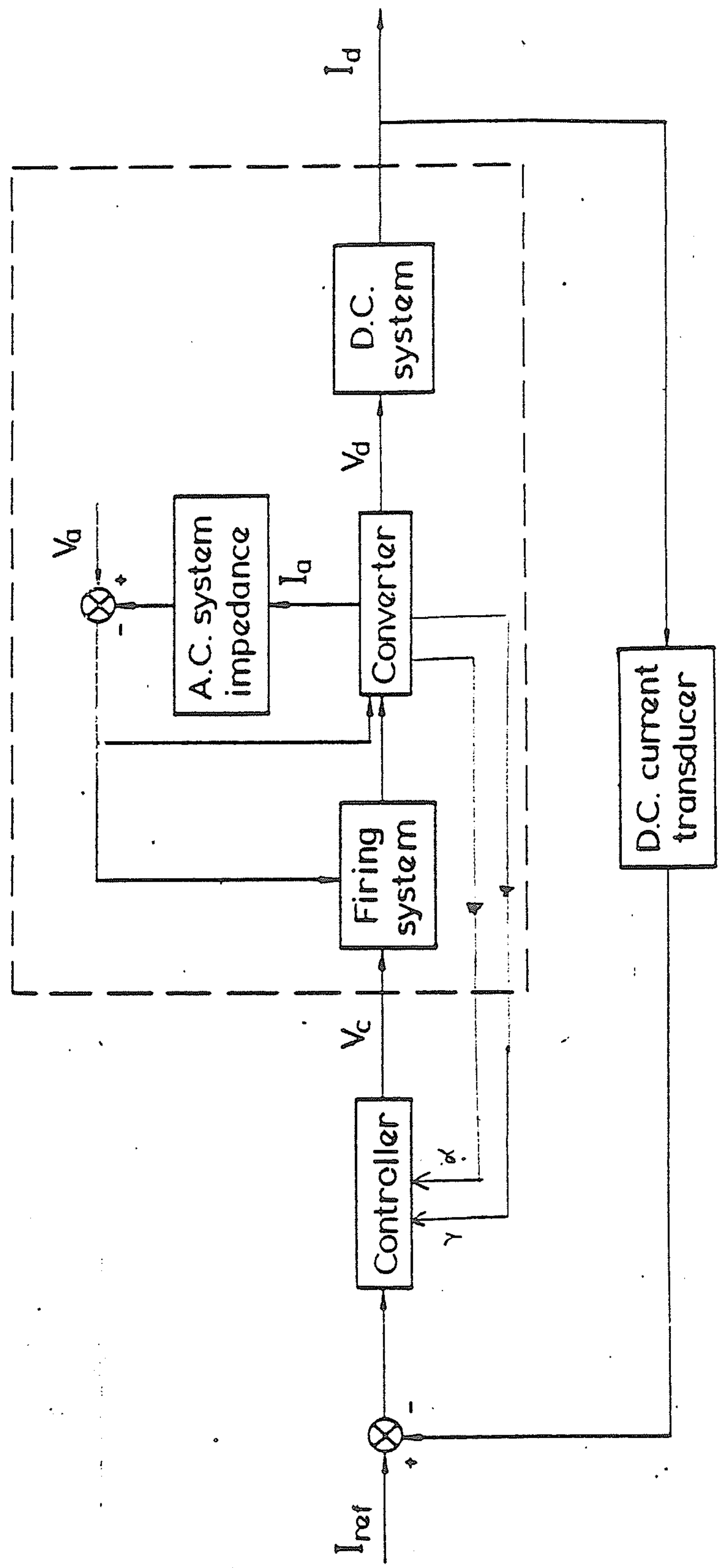


Figure 4.7: Feedback control of HVDC system.

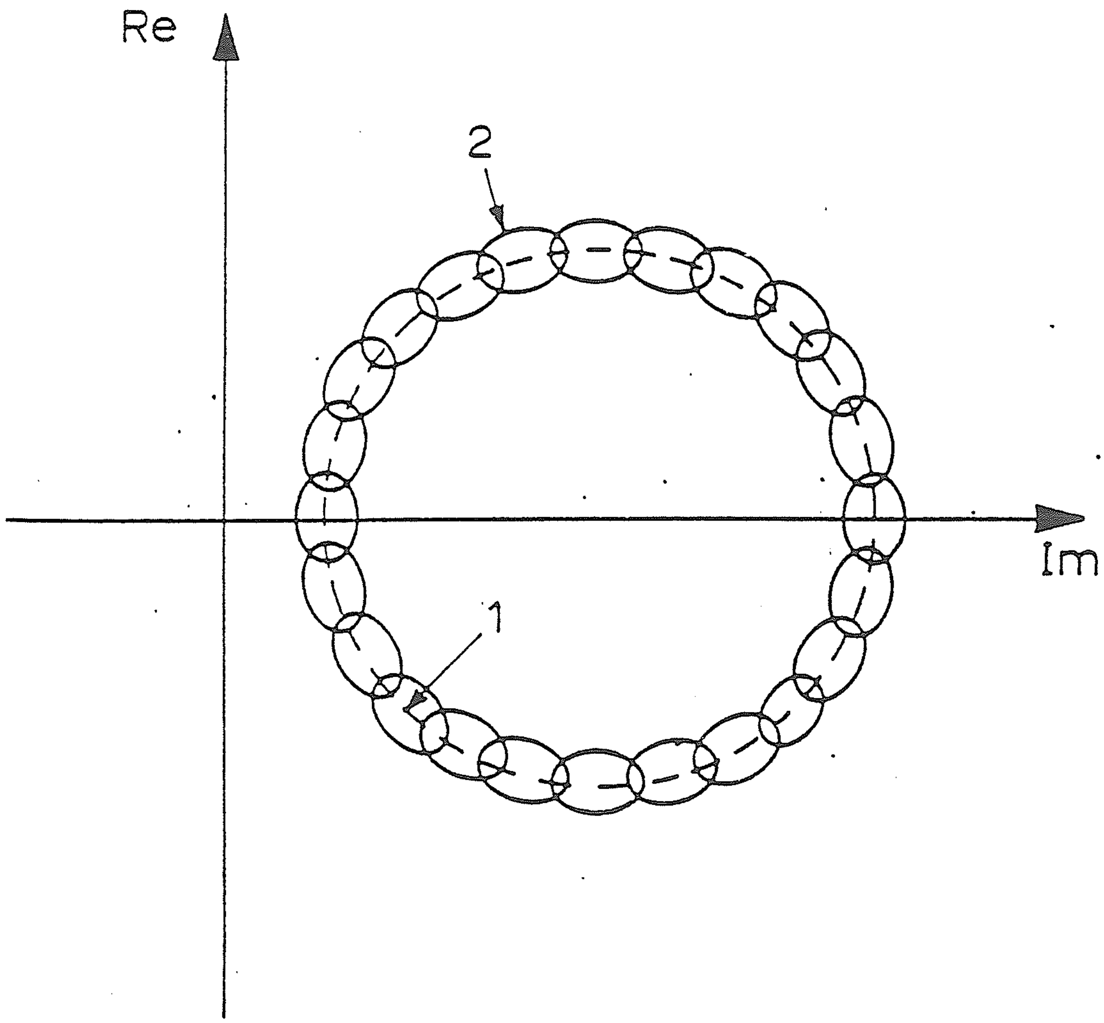


Figure 4.8: Example of double-input Describing Function plot [12]
1: Simple input Describing Function w_1 and amplitude V_{m1}. 2: Double-input Describing Function at frequency w_1, amplitude V_{m1}, for a bias signal of amplitude V_{m2} and frequency

α^0. Also note the control loop of the converter is open, when we are measuring the Describing Function of the HVDC converter. The Describing Function for HVDC converter also depends on the amplitude, frequency and phase of the input signal. Most of the steady-state parameters of the HVDC converter could be obtained from a load flow study.

As the *Modulation Signal generator* block of the digital transfer function analyzer generates a signal whose mean value is zero, a dc level must be set independently. Also, the modulating signal generation block must be equipped with providing the necessary phase delay in reference to the ac bus voltage. The phase shifting circuit must be able to handle full 360 degrees.

The input to the correlator is the current waveform, α response and γ response, although in the figure, the procedure for dc current waveform is fully explained. If the direct current measuring transducer has intrinsic dynamics, the phase shift due to such dynamics should be taken into account.

4.9 Feedback System with Multiple Nonlinearity

It is quite possible [15] that nonlinearities will be present at more than one station and at more than one control loop. In fact, the particular combination of nonlinear error transducer and nonlinear power element are common occurrences in control system applications, and this is certainly the case with HVDC system.. Thus it is quite fitting that we extend the procedure of using Describing Function technique in the study of multiple nonlinear systems.

4.9.1 Multiple Nonlinearity System

In general a two nonlinear system is shown in figure 4.10, where $N_1(x_1, X_1^{\cdot})$ and $N_2(x_2, X_2^{\cdot})$ are the nonlinear elements and $L_1(s)$ and $L_2(s)$ are the linear element present in the feedback loop. Let us represent the two nonlinearities by their respective Describing Functions $N_1(A_1, w)$ and $N_2(A_2, w)$. The frequency response of this system can be determined by the solution of the equation

$$\frac{X_1}{R}(jw, A) = \frac{1}{1 + N_1(A_1, w)L_1(jw)N_2(A_2, w)L_2(jw)} \tag{4.24}$$

provided that the use of the Describing Function is permissible. Clearly the requirement for this to be true is that $L_1(jw)$ and $L_2(jw)$ are each low-pass filters, so that inputs to both the non- linearities are nearly sinusoidal.

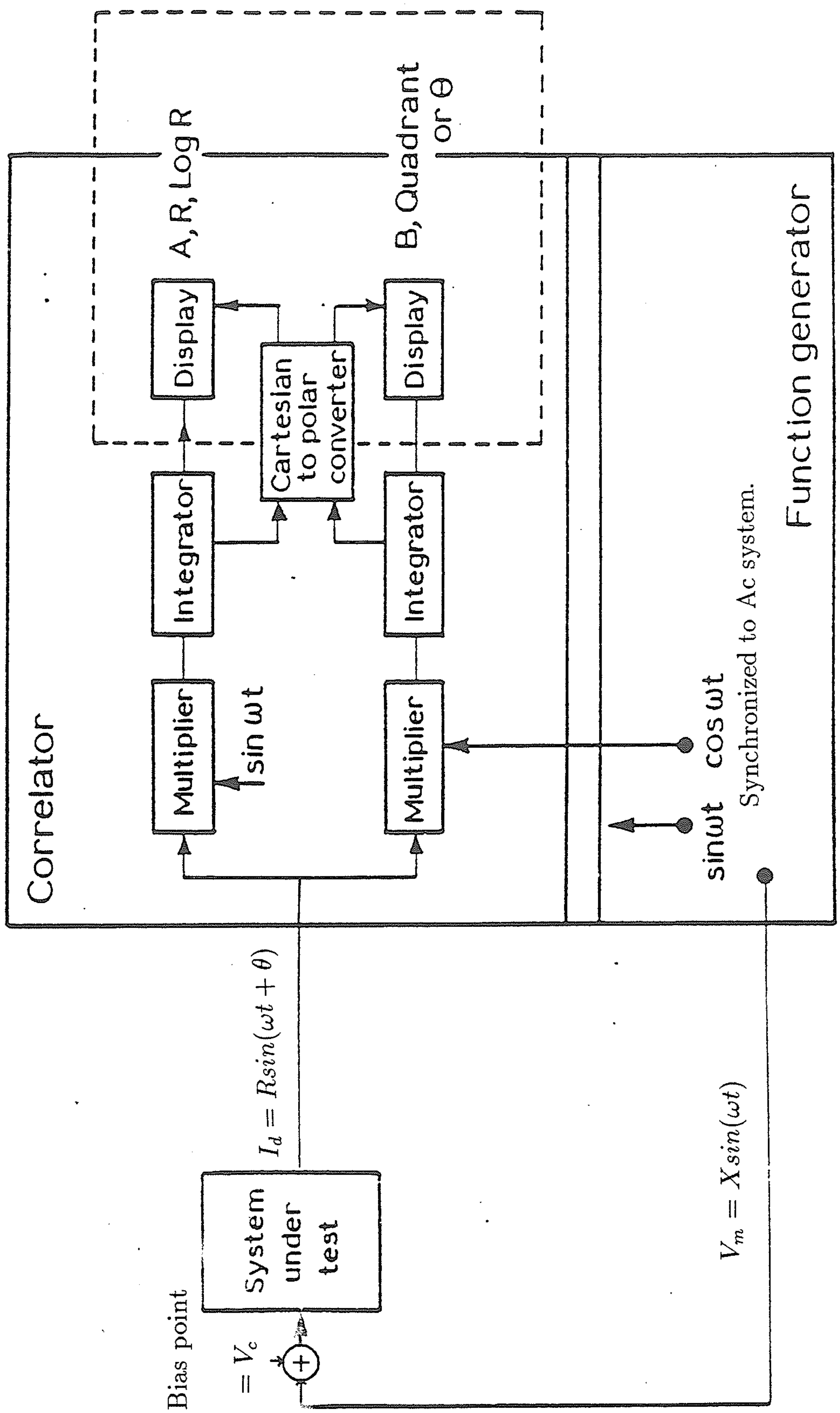


Figure 4.9: Schematic diagram of the determination of Describing Function for HVDC converter using EMTDC

Limit cycle study for this system corresponds to the determination of non-trivial solutions to the set of four relationships.

$$\begin{bmatrix} N_1 & -1 & 0 & 0 \\ 0 & L_1 & -1 & 0 \\ 0 & 0 & N_2 & -1 \\ 1 & 0 & 0 & L_2 \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \\ X_2 \\ Y_2 \end{bmatrix} = 0$$

Or equivalently

$$\det \begin{vmatrix} N_1 & -1 & 0 & 0 \\ 0 & L_1 & -1 & 0 \\ 0 & 0 & N_2 & -1 \\ 1 & 0 & 0 & L_2 \end{vmatrix} = 0$$

Which reduces to the single equation

$$1 + N_1(A_1, w)L_1(jw)N_2(A_2, w)L_2(jw) = 0 \tag{4.25}$$

Of course, we come to the same conclusion by setting the denominator of 4.29 to zero, corresponding to writing the characteristic equation for the purely linear case. The above equation can be solved by any of the techniques of the limit cycle determination. We can treat the quantity $N_1(A_1, w)L_1(jw)N_2(A_2, w)$ as an equivalent single nonlinearity $N(A_1, w)$. When $L_1(jw)$ is a low-pass function, this simplified approach will be in small error. On the other hand, should $L_1(jw)$ turn out to be a lead-lag or similar non-low-pass compensation network, the simplified approach could lead to large error.

A more accurate solution to both the frequency response and limit cycle problems can be had by computing the Describing Function for the complete chain $N_1(x_1, \dot{x_1})L_1(jw)N_2(x_2, \dot{x_2})$. This is accomplished by determining the actual first harmonic in Y_2 when x_1 is pure sinusoid. It is, of course, a more difficult approach. Regarding this approach, we observe that even if N_1 and N_2 are only amplitude dependent, N will be both amplitude and frequency dependent because of the presumed frequency dependence of L_1. Thus, in general, the treatment of multiple nonlinearity systems is bound to be some what more laborious than the treatment of single nonlinearity systems.

4.10 Limit Cycle Analysis of Multi-terminal HVDC System

The above procedure could be easily extended and applied to the Nelson River Multi-terminal System. A schematic diagram of the Nelson River multi-terminal system is shown in figure 4.11. Note that in this case dc filters are neglected, however they could be easily included for a complete analysis. in general, such filters include additional complexity, but the procedure for the limit cycle analysis remains virtually unchanged. Note that in this figure N_1 and N_2 refers to the Describing Functions of bipole 1 and

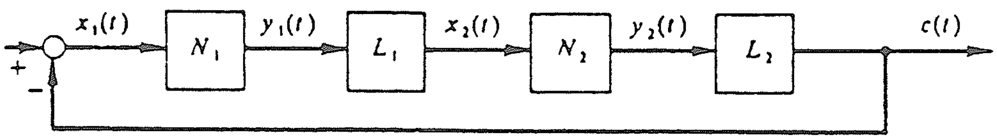


Figure 4.10: Multiple nonlinearity feedback system

bipole 2 respectively. Similarly, N_3 refers to the Describing Function of the rectifier. C_1 and C_2 refers to the combined pole and group controller. For the present treatment they are assumed to be linear but they could nonlinearities, and the procedure for evaluating limit cycle oscillations remains the same regardless of their presence. L_1 and L_2 represents the smoothing inductors of bipole 1 and bipole 2 and L_3 represents the total of line inductances and the smoothing rector of the rectifier. I_{ref1} and I_{ref2} represents the current order of bipole 1 and bipole 2 and I_{ref3} represents the current order of the rectifiers.

For the above multi-terminal system the following equations hold.

$$\frac{V_1 - V_2}{L_1 s} + \frac{V_3 - V_2}{L_2 s} + \frac{V_4 - V_2}{L_3 s} = 0 \tag{4.26}$$

$$X_2 = C_1 X_1 \tag{4.27}$$

$$-\frac{V_1 - V_2}{L_1 s} = X_1 \tag{4.28}$$

$$\frac{V_1 - V_2}{L_1 s} = N_1 X_2 \tag{4.29}$$

$$X_3 = C_2 X_4 \tag{4.30}$$

$$-\frac{V_3 - V_2}{L_2 s} = X_4 \tag{4.31}$$

$$\frac{V_3 - V_2}{L_2 s} = N_2 X_3 \tag{4.32}$$

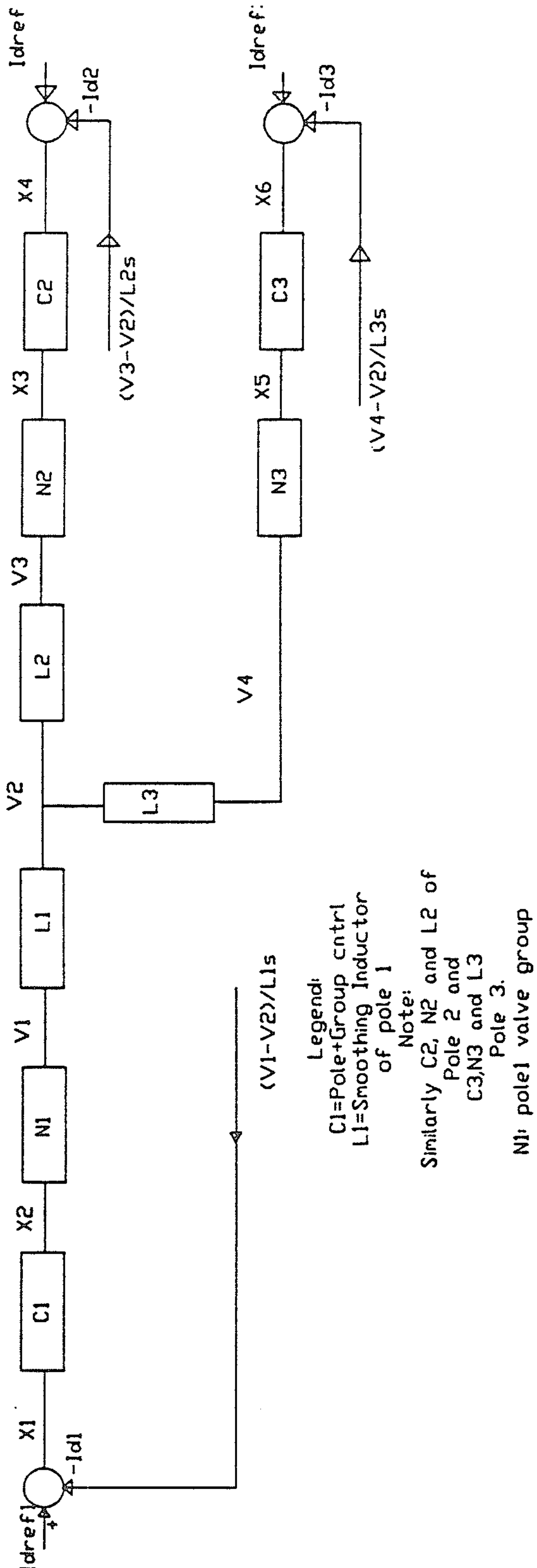


Figure 4.11: Nelson River multiterminal HVDC system.

$$\frac{V_4 - V_2}{L_3 s} = N_3 X_5 \tag{4.33}$$

$$X_5 = C_3 X_6 \tag{4.34}$$

$$-\frac{V_4 - V_2}{L_3 s} = X_6 \tag{4.35}$$

The above equations could be reformulated as

$$C_1 X_1 - X_2 = 0 \tag{4.36}$$

$$X_1 + \frac{V_1}{L_1 s} - \frac{V_2}{L_1 s} = 0 \tag{4.37}$$

$$N_1 X_2 - \frac{V_1}{L_1 s} + \frac{V_2}{L_1 s} = 0 \tag{4.38}$$

$$X_3 - C_2 X_4 = 0 \tag{4.39}$$

$$X_4 + \frac{V_3}{L_2 s} - \frac{V_2}{L_2 s} = 0 \tag{4.40}$$

$$N_2 X_3 - \frac{V_3}{L_2 s} + \frac{V_2}{L_2 s} = 0 \tag{4.41}$$

$$N_3 X_5 - \frac{V_4}{L_2 s} + \frac{V_2}{L_3 s} = 0 \tag{4.42}$$

$$X_5 - C_3 X_6 = 0 \tag{4.43}$$

$$X_6 + \frac{V_4}{L_3 s} - \frac{V_2}{L_3 s} = 0 \tag{4.44}$$

$$\frac{V_1}{L_1 s} - \frac{V_2}{L_1 s} + \frac{V_3}{L_2 s} - \frac{V_2}{L_2 s} + \frac{V_4}{L_3 s} - \frac{V_2}{L_3 s} = 0 \tag{4.45}$$

The above 10 equation could be represented in the matrix form as

$$\begin{bmatrix} C_1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_1 s} & -\frac{1}{L_1 s} & 0 & 0 \\ 0 & N_1 & 0 & 0 & 0 & 0 & -\frac{1}{L_1 s} & \frac{1}{L_1 s} & 0 & 0 \\ 0 & 0 & 1 & -C_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & -\frac{1}{L_2 s} & \frac{1}{L_2 s} & 0 \\ 0 & 0 & N_2 & 0 & 0 & 0 & 0 & \frac{1}{L_2 s} & -\frac{1}{L_2 s} & 0 \\ 0 & 0 & 0 & 0 & N_3 & 0 & 0 & \frac{1}{L_3 s} & 0 & -\frac{1}{L_3 s} \\ 0 & 0 & 0 & 0 & -1 & C_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 170 & -\frac{1}{L_3 s} & 0 & \frac{1}{L_3 s} & \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_1 s} & -\frac{1}{L_1 s} - \frac{1}{L_2 s} - \frac{1}{L_3 s} & \frac{1}{L_2 s} & \frac{1}{L_3 s} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \\ V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = 0$$

Now for the column vector $Z = (X_1, X_2, X_3, X_4, X_5, X_6, V_1, V_2, V_3, V_4)^T$ to have non-trivial solution, the necessary condition is

$$\det \begin{vmatrix} C_1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_1 s} & -\frac{1}{L_1 s} & 0 & 0 \\ 0 & N_1 & 0 & 0 & 0 & 0 & -\frac{1}{L_1 s} & \frac{1}{L_1 s} & 0 & 0 \\ 0 & 0 & 1 & -C_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & -\frac{1}{L_2 s} & \frac{1}{L_2 s} & 0 \\ 0 & 0 & N_2 & 0 & 0 & 0 & 0 & \frac{1}{L_2 s} & -\frac{1}{L_2 s} & 0 \\ 0 & 0 & 0 & 0 & N_3 & 0 & 0 & \frac{1}{L_3 s} & 0 & -\frac{1}{L_3 s} \\ 0 & 0 & 0 & 0 & -1 & C_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 170 & -\frac{1}{L_3 s} & 0 & \frac{1}{L_3 s} & \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_1 s} & -\frac{1}{L_1 s} - \frac{1}{L_2 s} - \frac{1}{L_3 s} & \frac{1}{L_2 s} & \frac{1}{L_3 s} \end{vmatrix} = 0$$

This is essentially the limit cycle existence criteria of the multiterminal HVDC system. Since the determinant is a 10*10 matrix, it could be easily solved by symbolic or numeric computation.

In general the above determinant produces 10th order polynomial equation, involving the system unknowns, whose nature is being investigated. Such parameters could be controller gain time constant limit cycle frequency and in general any of the design parameters of the controller and the converter. The 10th order complex equation could be readily solved by using numerical root finding methods of complex polynomial, the above program also could be readily solved as the nonlinear constrained optimization problem. In case a valid solution is obtained, then there should exist a limit cycle oscillation in the system. However this limit cycle oscillation could be stable or unstable. It is the existence of stable limit cycle that are trouble some, since the controller design objective is to avoid these limit cycles. Moreover there could be multiple solutions. These are indication that the system being considered has multiple limit cycle oscillation modes. In short the above Describing Function method of stability formulations provide complete solutions to system stability. However, the above formulation cannot alone determine whether the limit cycle oscillations are stable or not.

4.11 Summary

EMTDC is an extremely useful simulation software for digital simulation and in particular for the evaluation of the Describing Function of the HVDC converter. In this chapter, the dual input describing function has been extended to multiterminal HVDC converters and an analytical criteria has been established for limit cycle oscillation of multiterminal HVDC converters. Application of such Describing Function theory, however, was not carried out due to lack of time.

Some other properties of the describing Function as applicable to HVDC converters are listed below for completeness. The interested reader is advised to refer [12] for further details.

The Describing Function for a HVDC converter is a closed curve. However, when the amplitude of the modulating signal is small, the Describing Function degenerates into a point in the complex plane. As the amplitude of the modulating signal becomes large, the Describing Function develops into a closed curve. When the short-circuit ratio of the ac side is high, the trajectory of the Describing Function for various values of the modulating amplitude remains centered at the origin of the complex plane. However, when the short-circuit ratio of the ac side is small, the origin of the Describing Function tends to drift considerably from the origin of the complex plane. Moreover, when the short-circuit ratio of the ac side is low and the ac voltage has considerable negative harmonics- fundamental or second harmonics – the resulting Describing Function is considerably bigger. This enlargement of the Describing Function suggests that when ac side has negative sequence voltage combined with low short-circuit ratio the HVDC converter is more susceptible to limit cycle oscillations.

In conclusion, it is my opinion that analytical techniques such as Describing Function could be combined with the off-line digital simulation program EMTDC and the results could be verified with the analog or digital simulator. Such two step procedure will provide, in my opinion, valuable insight to HVDC control design, analysis and evaluation of system performance.

Chapter 5

Conclusion and Recommendation

5.1 Conclusion

This thesis shows that proper modelling of an operating dc system with a digital simulation program can result in an useful facility for studying control behaviour of the real system.

This thesis address a number of factors relevant to digital simulation and these are as follows:

(a) Complexity of system modelling- by a judicious investigation of the phenomena to be modelled, the system can be simplified. Since there was no oscillation in the paralleled inverter line current, we modelled the rectifier as a dc source with controls. Similarly, HVDC inverters were modelled as six pulse bridges since for the present study we were concerned with low frequency oscillations.

(b) Converter controls had to be modelled in details at the electronic level. It was not sufficient to use generic controls for this purpose.

(c) Various control modification concepts could be easily investigated once the operating HVDC system is modelled properly.

(d) An analytical approach was attempted where the well known Describing Function techniques was extended to multiterminal DC transmission systems. However, detailed testing of the approach was considered outside the scope of the thesis.

5.2 Recommendation

The Describing Function approach appears promising and should be further investigated.

Bibliography

[1] D. P. Atherton, *Nonlinear Control Engineering*, Van Nostrand Rehinhold, 1982

[2] J. K. Aggarwal, M Vidyasagar, *Nonlinear System Stability Analysis*, Dowden, Hatchison & Ross, Inc, 1977.

[3] S. Arabi and M. Z. Tarnawacky, *A Diode Rectifier Series Tap on an HVDC Lines* IEEE Trans. PAS , Volume PAS-104, No. 9, pp 2540-2546. Sept-85.

[4] J. D. Ainsworth, *The Phase-Locked Oscillator - A New Control Method for Controlled Static Converters.* IEEE Transction, Vol PAS-87, 1968, pp 859-865.

[5] J. D. Ainsworth, *Core Saturation Instability in the Kingsnorth HVDC link*, CIGRE Study Committee No 14, Winnipeg, Manitoba, Canada, June 20-24, 1977.

[6] D. Brandt, I.H. Mckay, M.M. Rashwan, S.T. Ranade, *Paralleling and Deparallelling tests on Nelson River HVDC Bipole 1 & 2*, IEEE Trans. PAS , Vol PAS-1103, No 4, April 1984.

[7] F. Busemann, *The Theory of the Control Problem of HVDC Transmission With Rectifiers and Inverters in Bridge Circuit.* E.R.A Report No Z/T74, 1948.

[8] N. A. Bjaresten, *The Static Converter as a High-Speed Power Amplifier.* Direct Current, Vol 8, 1963, pp 154-165.

[9] C. T. Chen, *One Dimensional Digital Signal Processing*, ISBN 0824768779.

[10] *EMTDC User's Manual*, Version 1.0, Manitoba HVDC Research Centre, 1986, pp 762-76.

[11] Kjell Erikson, Gote Liss, Erik V. Persson, *Stability Analysis of the HVDC Control System Transients Using Theoretically Calculated Nyquist Diagrams* . IEEE Trans, PAS 90 No 516 May/June 1970, pp 733-739.

[12] J. M. Ferreira de Jesus, L. L. Freris, J. P. Sucena-Paivȧ, *Describing Function Applied to HVDC system Harmonic Instability*, IEE Proceedings, Vol 134, pt C, N0 2, March 1987.

[13] K. G. Fehrle and R. H. Lasseter, *Simulation of Control Systems and Application to HVDC Converters*, IEEE Tutorial Course on Digital Simulation of Electrical Transient Phenomena, Chapter vi, pp 47-54, Course text 81EH0173-5-PWR, 1981.

[14] F. Fallside, C. J. Goodman and R. D. Jackson, *Stability of first-order sampling and thyristor systems*, Electronic Letters, Vol 50, 1969, pp 566-567.

[15] Arther Gelb, Wallace E. Vander Velde, *Multiple-Input Describing Function and Nonlinear System Analysis*, Magrew Hill Book Company, 1968.

[16] Gonzalez and Wintz, *Digital Image Processing* , Prentice Hall 1989.

[17] M. D. Heffernan, K. S. Turner, J. Arrillaga, and C. P. Arnold, 1981, *Computation of AC-DC System Disturbances, Parts I, II and III*, IEEE Transactions on Power Apparatus and systems , vol PAS-100, No. 11, pp 4341-4363, Nov. 1981.

[18] P. A. Hazell and J. O. Flower, *Stability Properties of Certain Thyristor Bridges Control System. Part 1- the Thyristor Bridge as a Discrete Control System. Part 2- The Interrelationship of Discrete and Continuous-Design Method s.* Proc IEE, Vol 117, 1970, pp 1405-1420.

[19] Houpies, Constantine, H, *Digital Control System -Theory, Hardware, Software* Magrew Hill, New York, 1988.

[20] T. Ino, R. M. Mathur, M. R. Iravani, and S. Sasaki, 1985, *Validation of Digital Simulation of DC Links - Part II,* IEEE Trans. PAS, Volume PAS-104, No. 9, pp 2596, 2602, Sept-85.

[21] R. Jotten et al, *Control in HVDC Systems: The State of the Art. Part 1 - Two Terminal Systems.* paper 14-10, CIGRE - 1978.

[22] E. W. Kimbark, *Direct Current Transmission - Volume 1.* Wiley Interscience, 1971.

[23] Benjamin C. Kuo, *Digital Control System*, SRL Publishing Company, 1977.

[24] R. von Lutz, *Bestimmung des ststionaren Betriebserhaltens von Stromrichterschaltungen mittels Newton-Verfahren* , Archiv for Elektrotechnik 68 (1985) 355-363.

[25] R, von Lutz, Manfred Grotbach, *Straightforward Discrete Modelling for Power Converter Systems*, IEEE , PAS 1985, pp 761- 770.

[26] Fred C. Y. Lee, Ralph P. Iwens, Yuan Yu, James E. Twins, *Generalized Computer Aided Discrete Time-Domain Modelling and Analysis of DC-DC Converter*, IEEE Transaction on Industrial Electronics and Control Instrumentation, Vol, IECI-26, No 1, May 1979.

[27] R. Hernendez Miller, J. P. Sucena-Paiva , L. L. Freris, *Modelling of Controlled Rectifiers in Feedback Systems* , IEEE , PES Summer Meeting and EHV/UHV Conference, Vancouver , B.C. 1973. pp 167-175.

[28] Yi-xin Ni and A. A. Faoud, *A Simplified two-terminal HVDC Model and its use in Direct transient stability Assessment*, IEEE, PES 1987, pp 1006-1012.

[29] S. Nyati, S.R. Atmuri, V. Koschik, R.M. Mathur and D. Flueckiger, *Comparison of Voltage Control Devices at HVDC Converter Stations Connected to Weak AC systems*, IEEE PAS winter meeting, New Orleans, 1987, Paper No. 87WM 159-7.

[30] K. Ogata, *Modern Control System* Prentice Hall, 1978.

[31] Erik V. Persson, *Calculation of Transfer Function in Grid Controlled Converter System, With special Reference to HVDC Transmissions*, Proc, IEE Vol 6117p.

[32] Rabiner and Gould, *Theory and Application of Digital Signal Processing*, Prentice Hall, 1975.

[33] J. Reeve and S. P. Chen , *Digital Simulation of Multiterminal HVDC Transmission Systems*, IEEE Transactions on Power Apparatus and Systems , vol PAS-103, No. 12, pp 3634-3644, Dec 1984.

[34] J. P. Sucena-Paiva and L. L. Freris, *Stability of a DC Transmission Link Between Strong AC System*, Proc. IEE, Vol 120, No 10, October 1973, pp 1233-1242.

[35] J. P. Sucena-Paiva, R. Hernandez and L. L. Freris, *Stability Study of Controlled Rectifiers Using a New Discrete Model*, Proc, IEE, Vol 119, No 9, September 1972. pp 1285-1293

[36] J. P. Sucena-Paiva and L. L. Freris, *Stability of a D.C. Transmission Link Between Weak A.C. System*, Proc, IEE, Vol 121, No 6, June 1974.

[37] J. P. Sucena-Paiva and L. L. Freris, *Stability of Rectifiers with Voltage Controlled Oscillator firing System*, Proc- IEEE, Vol 120, No 6, June 1973.

[38] T. Shome, *Real-time Valve group implementation on HVDC Simulator*, Prepared for Manitoba HVDC research Center, contract no E 4.84-1

[39] T. Shome, *Generalized Real-time Machine Model Implementation on HVDC Simulator* , Prepared for Manitoba HVDC research Center, Contact no E 4.84-2.

[40] Tapas Shome, A. M. Gole, Dennis Brandt, Bob Hamlin, *Adjusting Multiterminal Converter Controls using Digital Simulation Program* , IEEE Summer Power Meeting, 1989.

[41] J. P. Sucena-Paiva, *A Steady-state Stability Study of Converters and High Voltage D.C. Transmission System.* Phd thesis, University of London, 1972.

[42] J. P. Sucena-Paiva, R. Hernandez and L. L. Freris, *Stability Study of Controlled Rectifiers Using a New Discrete Model*, proc IEE, Vol 119, No 9, pp 1285-1293, September 1972.

[43] T. Sakurai, J. Ohara, J. Ueda, A. Mase, T. Horuchi and J. Arai, *A Study of a Certain a.c. Oscillations of HVDC System.* paper A79 100-9, IEEE Power Engineering Society Winter meeting, Newyork, February 1979.

[44] T. Shome, *Phase Lock Loop (PLL) and HVDC Converter* , Private communication between Dr. A. M. Gole and T. Shome

[45] Hilmi M. Turanli, Robert W. menzies and Dennis A. Woodford. *Feasibility of DC Transmission with Forced Commutation to Remote Loads,* (83SM 466-0); IEEE Trans. PAS, pp 1256-1263. June 84.

[46] M. Z. Ternawacky. *Course Notes of HVDC I and II* , University of Manitoba, Winnipeg, Manitoba, Canada.

[47] E. Uhlmann, *Power Transmission by Direct current.* Springer-Verlag, 1975.

[48] M. Vidyasagar, *Nonlinear System Analysis* Prentice Hall, 1978.

[49] D. A. Woodford, A. M. Gole, and R. W. Menzies, *Digital Simulation of DC Links and AC Machines*, IEEE Transactions on Power Apparatus and Systems , vol PAS-102, No. 6, pp 1616-1623, June 1983.

[50] D. A. Woodford, *Validation of Digital Simulation of DC links,* IEEE Trans. PAS , Volume PAS-104, No. 9, pp 2588-2594, Sept-85.

[51] R. Yacamini, J. C. de Oliveira, *Instability in HVDC System at Low Order Harmonics*, IEE Proc, Vol 127, Pt. C, No 3, May 1970, pp 179-188.

[52] R. Yacamini, J. C. de Oliveira, *Harmonics Produced by Direct Current in Converter Transformers*, Proc IEE, Vol 125 No 9, September 1978.

[53] R. Yacamini and W. J. Smith, *Negative Sequence of Converters*, Proc IEE, Vol 128 pt B No 3, May 1981, pp 161-166.

Chapter 6

Appendix

Appendix A

The following is the list of PGB and VARS that are used in the Multi-terminal HVDC simulation study.

1. PGB(1)= Measured α of inverter one.
2. PGB(2)= AC side voltage.
3. PGB(3)= Total Rectifier direct current.
4. PGB(4)= Inverter one dc voltage.
5. PGB(5)= AC side receiving current
6. PGB(6)= Inverter 2 dc voltage
7. PGB(7)= Inverter 1 and Inverter 2 DC tie voltage.
8. PGB(8)= Rectifier α order for the pole controller
9. PGB(9)= Inverter 1 commutation failure indicator
10. PGB(10)= Inverter 1 gamma measured.
11. PGB(11)= Delta Gamma error of pole controller 2.
12. PGB(12)= Measured α of inverter 2.
13. PGB(13)= Gamma measured of inverter 2.
14. PGB(14)= Inverter 2 direct current.
15. PGB(15)= Inverter 1 direct current.
16. PGB(16)= Inverter 1 pole controller alpha output.
17. PGB(17)= Inverter 1 valve group controller output alpha order.
18. PGB(18)= Inverter 2 alpha order output of pole controller.

19. PGB(19)= Inverter 2 valve group controller output alpha.
20. PGB(20)= Inverter 1 delta gamma error output of pole controller.

1. VAR(1)– AC receiving side system voltage
2. VAR(2)– DCCT measurement time constant for rectification.
3. VAR(27)– Y_L for POL1C7 of rectifier.
4. VAR(24)– DCCT measurement time delay for bipole 1 (POL1C7)
5. VAR(3)– Current order to rectifier.
6. VAR(4)– Rectifier open circuit dc voltage.
7. VAR(16)– Current margin for bipole 1
8. VAR(18)– Voltage margin or POL1C7
9. VAR(20)– Y_s for POL1C7 of bipole 1.
10. VAR(22)– Y_L of POL1C7 of bipole 1 (Proportional Gain)
11. VAr(8)– Transformer base MVA of pole 1.
12. VAR(10)– Rated secondary side AC line to line pole 1 RMS voltage.
13. VAR(6)– Per unit transformer turns ratio DC side/AC side.
14. VAR(25)–DCCT measurement time constant for bipole 2.
15. VAR(17)– Bipole 2 current Margin.
16. VAR(19)– Per unit DC voltage due to current margin for bipole 2.
17. VAR(21)– Integral Gain– K_{R1} of bipole 2.
18. VAR(23)– Proportional gain K_{R2} of bipole 2.
19. VAR(9)– Transformer base rating in MVA of bipole 2.
20. VAR(11)– Rated secondary side (AC) line to line RMS voltage.
21. VAR(7)– Per unit transformer turns ratio DC side to AC side.
22. VAR(5)– Not used.
23. VAR(12)– Not used
24. VAR(13)– Not used.

25. VAR(14)– Not used

26. VAR(15)– Not used

27. VAR(26)– Not used

28. VAR(28)— POL1C7– Integral constant gain factor in radians for $\frac{31.3VAR(28)}{s}$ for integral gain α order to valve Group Controller.

29. VAR(34)– Modifying factor of the delta gamma gain characteristics of POL1C7(2.1VAR(34)).

Appendix B

The following listings contains the DSDYN, DSOUT and DATA file listings of the multiterminal HVDC system that was studied.

```
      subroutine dsdyn
c-----------------------------------------------------------------
c     revision date 14/07/1986.                                  |
c     0. according to bob hamlin's request line_side             |
      inductor is made 0.0h.                                     |
c     1. it was found that main amp of bipole 1 has              |
c     a dominant pole at 44.5 radians after neglegting           |
c     higher order terms for the dge(delta gamma error)          |
c     o/p.   maybe mosen's model used 68k ||.033uf.e             |
c     actual val on data sheet is 680k||.033uf.(dc135 amp)       |
c     2.there is no discontinous current forcing da to 155 deg   |
c     (the o/p of pole controller -bpl) so this portion of the   |
c     code is deleted.                                           |
c________________________________________________________________|__
c__________________________________________________________________|
c     this subroutine is used to simulate an ac_dc                 |
c     tie that assums two inverters are feeding the                |
c                                                                  |
c     ac receiving system.                                         |
c     two inverters are having parametrs exactly                   |
c     equal  to  radission's inverter 1&2                          |
c     a simple current controlled battery model is                 |
c     used for the rectifier.                                      |
c      usually inverter one is in cea control with .1pu margin     |
c     while inverter_2 is in current control with                  |
c     0.0 pu current margin.(or otherwise)                         |
c     a simple inductance  is assumed for the transmission         |
c     line of the system.                                          |
c     no ac filters are present at this point of time.             |
c     also no synchronous condensers are present on the            |
c     ac receiving side.                                           |
c__________________________________________________________________|
      real limit,intgl3,ldlag2
       include 'emte'
      common /s1/time,delt,ich,print
      common /s2/stor(5000),nexc/s3/gvlv(4,4,24)
      common /s4/var(100),con(100),pgb(25)
      common /carryit/ k1,k2
      save
c     create 230 kv 1_1 ac receiveing system
c
c
c
c____________________________________________________________________
      call esysl(1,4,5,6,var(1),377.0,0.0)
c__________________________________________________________________
c     initial blocking and deblocking is done here.
c     deblocking is done on inverter at t=0.05 s
c     and deblocking is done on rectifier at t=0.01 sec
c     after t=0.05 and between t=0.01 inverter is acting
c     as rectifier with -ve voltage to build   dc current on
c     dc link.
c_________________________________________________________________
      kbr=0
      kbi1=0
      kbi2=0
      amini=1.0
      aminr=0.0873
      if(time.gt.0.05) kbi1=1
      if (time .gt.0.11) kbi2=1
      if(time.lt.0.10) go to 10
      kbr=1
      amini=1.9
c     var(3) is current order to rectifier
c     accordingly current order to each inverter is .5var(3)
10    continue
```

```
c------------------------------------------------------------
c       blocking deblocking is over.
c____________________________________________________________
        c2=var(3)
        c1=realp2(0.5555,var(2),cdc(3,1,2))
        call pol2c5(c2,c1,0.0,0.1,aminr,2.7,0.5,0.3,dger,dar)
        yyx=(vdc(1,2)-vdc(3,2))/(1.8*1.7)
        yy1=realp2(1.0,0.001,yyx)
        call pol1c7(c2,c1,yy1,0.0,0.1,aminr,2.7,0.15,var(27),dger,dar)
        es(1,2)=var(4)*(cos(dar))*kbr
c____________________________________________________________
c  rectififer is modeled as controlled current voltage source es(1,2).
c____________________________________________________________
        c0=var(3)/2.0
c       var(14) and var(15) is current order to each inverter.
c____________________________________________________________
        c3=realp2(0.5555,var(24),cdc(2,5,2))
c       var(2) is the dc.ct. measurement delay.
        didt=1.11111*(vdc(5,2)-vdc(2,2))
        con(22)=realp2(1.0,0.001,didt)
c       alhpa [illegible]
        con(65)=float(k1+k2)
        ak1=4.273*con(65)
        ak2=difpl2(.01,ak1)
        con(66)=limit(0.0,26.0,ak2)
        x1=(var(16)-con(66))
        call pol1c7(var(14),c3,con(22),x1,var(18),amini,2.71
     & ,var(20),var(22),dgei,dai)
c       var(14)= p.u. current order.
c       var(16)=p.u. current margin.
c       var(18)=pu.incremental dc voltage defining current error.
c       var(20)=integral gain.
        var(22)= proportional gain.
       gmeax1=ldlag2(0.0345,0.001551,1.000,con(10))
c       t1 originally is 0.0345 -- bypass ldlag.
        dgex1=realp2(1.000,.98e-4,dgei)
        call vg1c36(dai,dgex1,k1,con(10),con(1),60.0,amini,2.70,
     &.314,aoi)
c       var(12)= pu. commutating reactance.
c       write(6,*)aoi,kbi,con(1),con(10),k1
c       ____________________________________________________
c                                                            |
c                                                            |
c                                                            |
c       valve group of first inverter.                       |
c       points to note -------                               |
c       nv=0 since first valve group                         |
c       saturation of the transformer is clipped so          |
c       k1=-1.2                                              |
c       z0=1.6 pu ie. zero sequence impedence so we assume   |
c       star star with imbeded delta.                        |
c       current margin=.2 pu                                 |
c       scale factor=3.0 since 3 such system are in series.  |
c       delta gamma error slope of valve group controller    |
c       =0.1 pu.                                             |
c       con(10) is inv1 measured gamma angle in radians.     |
c                                                            |
c                                                            |
c____________________________________________________________|
       call b6pl10(2,1,2,3,1,2,0,2,var(8),230.0,var(10),var(6),0.5,
     +0.4,-1.2,0.2,1.6,aoi,0.05,60.0,kbi1,1,1,con(1),con(10),k1,
     +1460.0,0.0867,1.0,0.1,3.0)
c       var(8)=tr base mva
c       var(10)=sec ac volts.
c       var(6)=inv1 pu. transformer turns ratio.
        c4=realp2(0.555,var(25),cdc(4,6,2))
```

```
c       for inverter of  bipole 2 imax=1800 amps
        call polc12(var(15),c4,var(17),var(19),amini,2.71,var(21)
     &,var(23),0.12,0.0,dgei2,dai2)
c       var(15)=pu. current order.
        var(17)=current margin.
c       var(19)=pu. incremental dc vol due to curr err.
c       var(21)=integral gain
c       var(23)= proportional gain.
        call vg2c18(dai2,dgei2,c4,con(13),60.0,amini,2.70,.314,aoi2)
c       var(6) is per unit inv2 transformer transfomation ratio
c       for constant current control var(11) must be >1.
c_____________________________________________________________________
c                                                                    |
c                                                                    |
c                                                                    |
c       this is the 2nd valve group of the parallel study.          |
c       points to note --------                                      |
c       nv=-1 since it is in parallel with inv1                      |
c       secondery ie converter side is 103.0 kv l-l                  |
c       accordingly a scale factor of 3.0 was utilised               |
c       to take into account star/star and star/delta                |
c       12 pulse case, as it is in bipole2.                          |
c       this inv2 is in  general constant current control.           |
c       so margin for the pole controller is 0.0 pu of               |
c       its load current.(or other wise)                             |
c____________________________________________________________________|
c_____________________________________________________________________
        call b6p110(2,1,2,3,1,4,0,2,var(9),230.0,var(11),var(7),
     &  0.5,0.4,-1.2,0.2,1.6,aoi2,0.05,60.0,kbi2,1,-1,con(12),
     &  con(13),k2,1460.0,0.0867,1.0,0.1,3.0)
c       var(7)= inv2  pu. transformer turns ratio.
c       var(9)=transformer base mva.
        var(11)= sec ac vol of transformer.
        inv2 transformer is star star with imbeded delta assumed
c       nv=0 for the second case
c       con(12)= mitered  alpha of inv,con(13) =mitered gama of
c       inv2,k2= commutation fail indicator.
c_____________________________________________________________________
c                                                                    |
c                                                                    |
c                                                                    |
c       channel 2 is rectifier side voltage.                         |
c       channel 3 is total dc link current supplied by rectifier.    |
c       channel 4 is inv _2 voltage ie back emf.                     |
c       channel 5 is ac receiving system phase 1 (square)current.    |
c       channel 6 is inv2 side dc voltage ie back emf.               |
c       channel 1 is inv1's alpha measured.                          |
c       channel 7 is inv 1&2 tie point dc voltage.                   |
c       ch 8 is rectifier alpha order from pole controller.          |
c____________________________________________________________________|
        con(2)=vdc(1,2)
        con(3)=cdc(3,1,2)
        con(4)=vdc(2,2)
        con(5)=ccin(1,1)
        con(6)=vdc(4,2)
        con(7)=vdc(3,2)
        con(8)=dar*57.3
        con(14)=c4
c       channel 14 is inv2 dc current
        con(15)=c3
        channel 15 is inv1 d current
        channel 13 is  inv2 gamma measured
c       channel 9 is inv1 commutation failure indicator
c       channel 11 is inv2 delta gamma o/p of polecontroller2.
c
c
```

```
c
c
      con(17)=aoi*57.3
c     ch 17 is inv1 valve group controller alphaorder output.
      con(18)=dai2*57.3
c     ch 18= inv2 alpha order out of pole controller
      con(19)=aoi2*57.3
c     ch 19 is inv2 valve group controller alpha order output.
      con(20)=dgei*57.3
c     inv1 dge of ie output of pole controller.
      con(16)=dai*57.3
c     inv1 pole controller output alpha
      con(21)=dgei2*57.3
c     it is delta gamma error of inv2 pole controller.
      return
      end
      subroutine dsout
      real limit,intgl3,ldlag2
       include 'emte'
      common /s1/time,delt,ich
      common /s2/stor(5000),nexc/s3/gvlv(4,4,24)
      common /s4/ var(100),con(100),pgb(25)
      common /carryit/k1,k2
      pgb(1)=con(1)*57.3
      pgb(2)=con(2)
      pgb(3)=con(3)
      pgb(4)=con(4)
      pgb(5)=con(5)
      pgb(6)=con(6)
      pgb(7)=con(7)
      pgb(8)=con(8)
      pgb(9)=k1
      pgb(10)=con(10)*57.3
      pgb(11)=con(21)
c     ch 11  is delta gamma error (output signal )of pole controller.
      pgb(12)=con(12)*57.3
c     con(12)=alpha measured of inv2
      pgb(13)=con(13)*57.3
c     con(13)=measured gamma of inv2
      pgb(14)=con(14)
c     con(14) is  inv 2 current
      pgb(15)=con(15)
      pgb(16)=con(16)
      pgb(17)=con(17)
      pgb(18)=con(18)
      pgb(19)=con(19)
      pgb(20)=con(20)
c     con(15) is inv1 dc current
      return
      end
    subroutine pol2c5(co,cd,cm,dv,amin,amax,gr1,gr2,dge,da)
c subroutine to model pole controls - one per pole
c   current error control amplifier included
c
c inputs
c    co = dc current ordered in pu (always +ve)
c    cd = dc current response in pu (always +ve)
c    cm = current margin in pu (+ve for inverter, 0 or -ve for rect)
c    dv = per unit incremental dc volts defining current error slope
c  amin = alpha min (eg: 5 deg for rect, 110 deg for inv) in rad
c  amax = alpha max (eg: 3.14 max) in rad
    gr1 = integral gain kr1   degrees/amp-sec  (+ve)
c   gr2 = proportional gain kr2    sec
c
c outputs
c   dge = delta gamma error (rad)
```

```
c     da = desired alpha (rad)
c
      common /s1/time,delt/s2/stor(5000),nexc
c  assume steady state initialization not required
      if (time.ge.delt) go to 5
      stor(nexc+2)=amin
      stor(nexc+1)=amin
c   to approximate slope of current error control
c   assume gamma = 18 deg, xc = 0.2 pu.
      stor(nexc+4)=0.0
      stor(nexc+5)=0.0
      if (cm.le.0.0) go to 5
      a1=dv
      if (dv.lt.0.0) a1=0.0
      if (dv.gt.0.2) a1=0.2
      stor(nexc+4)=2.1*a1/cm
c ** current control
    5 a1=cd-co
c  current summation and prop-int controller
      a5=(a1+cm)*31.42*gr1
      a6=stor(nexc+2)+0.5*delt*(a5+stor(nexc+3))
      a7=a5*gr2
      if (a6.lt.amin) a6=amin
      if (a6.gt.amax) a6=amax
      a6a=stor(nexc+2)
      stor(nexc+2)=a6
      stor(nexc+3)=a5
      stor(nexc+1)=a6a+a7
      da=stor(nexc+1)
      if (da.lt.amin) da=amin
      if (da.gt.amax) da=amax
c  current error control
      dcd=445.6*(cd-co-stor(nexc+5))
      a1=stor(nexc+5)+dcd*delt
      if (a1.gt.0.0) a1=0.0
      dge=stor(nexc+4)*stor(nexc+5)
      stor(nexc+5)=a1
      nexc=nexc+5
      return
      end
      subroutine pol1c7(co,cd,cdi,cm,dv,amin,amax,ys,yl,dge,da)
c  subroutine to model pole controls - one per pole
c    current error control amplifier included
c    this controller is specifically useful for bp1
c  *****************************************************
c******************************************************
c          note:  the information contained in this
c                 subroutine is developed by manufacturers
c                 and is considered their property and
c                 is not to be disclosed to anyone except
c                 employees of manitoba hydro or their
c                 duly authorised representatives.
c  *****************************************************
c******************************************************
c
c  inputs
c     co = dc current ordered in pu (always +ve)
c     cd = dc current response in pu (always +ve)
c     cdi= di/dt response in per unit (+ve & -ve)
c     cm = current margin in pu (+ve for inverter, 0 or -ve for rect)
c     dv = per unit incremental dc volts defining current error slope
c   amin = alpha min (eg: 5 deg for rect, 110 deg for inv) in rad
c   amax = alpha max (eg: 3.14 max) in rad
c     ys = smoothing control 0 - 1
c     yl = phase advance control for di/dt 0 - 1
c
```

```
c  outputs
c    dge = delta gamma error (rad)
c     da = desired alpha (rad)
c
      common /s1/time,delt,ich,print,fintim
      common /s2/stor(5000),nexc
      common /s4/var(100),con(100),pgb(25)
c  assume steady state initialization not required
      if (time.ge.delt) go to 5
      stor(nexc+2)=amin
      stor(nexc+1)=amin
c   to approximate slope of current error control
c   assume gamma = 18 deg, xc = 0.2 pu.
      stor(nexc+5)=0.0
      stor(nexc+6)=0.0
      if (cm.le.0.0) go to 5
      a1=dv
      if (dv.lt.0.0) a1=0.0
      if (dv.gt.0.2) a1=0.2
      stor(nexc+5)=2.1*a1/cm*var(34)
c
c ** current control
    5 a1=cd-co
c    di/dt  for gamma error control
      a3=(cd-stor(nexc+4))/delt
c    smoothing of di/dt for current controller
      cdii=stor(nexc+7)+delt*2000.0*(cdi-stor(nexc+7))
      stor(nexc+7)=cdii
c  current summation and prop-int controller
      a4=a1+cdii*0.3000*y1+cm
      a5=31.3*a4*var(28)
c       var(28) is the pu current to scale factor.
      a6=stor(nexc+2)+0.5*delt*(a5+stor(nexc+3))
      a7=a4*.5500*ys
      if (a6.lt.amin) a6=amin
      if (a6.gt.amax) a6=amax
      a6a=stor(nexc+2)
      stor(nexc+2)=a6
      stor(nexc+3)=a5
      stor(nexc+1)=a6a+a7
      da=stor(nexc+1)
      if (da.lt.amin) da=amin
      if (da.gt.amax) da=amax
c  discontinuous current forcing da to 155 deg for inverter
c       this portion is bypassed.
c     if (cd.gt.0.01) go to 20
c     if (amin.lt.1.745) go to 20
c     da=2.705
c     stor(nexc+2)=da
c     dge=0.0
c     stor(nexc+6)=0.0
c     go to 30
c
c  current error control
   20 a1=0.032*a3
      cd1=cd+a1
      dcd=44.56*(cd1-co-stor(nexc+6))*var(35)
      a1=stor(nexc+6)+dcd*delt
      if (a1.gt.0.0) a1=0.0
      dge=stor(nexc+5)*stor(nexc+6)
      if (dge.lt.-0.349) dge=-0.349
        orginal limit= -1.00 check dc 109 for details t.shome
      stor(nexc+6)=a1
      stor(nexc+4)=cd
      nexc=nexc+7
      return
```

```
      end
      subroutine vglc36(da,dge,cf,g,ar,f,amin,amax,gmin,ao)
c  subroutine to model valve group controls - 1 for each vg
c                  this model vco gain is different + shome..
   this model specifically represents the gamma control loop
   and alpha control loop of bp1 of the nelson river dc link.
c  ********************************************************
c**********************************************************
c            note:  the information contained in this
c                   subroutine is developed by manufacturers
c                   and is considered their property and
c                   is not to be disclosed to anyone except
c                   employees of manitoba hydro or their
c                   duly authorised representatives.
c  ********************************************************
c**********************************************************
c
c   inputs
c     da    = desired alpha from pole control (rad)
c     dge   = gamma error from pole control (rad)
c     cf    = commutation fail indicator (0=nofail, 1=fail)
c     g     = gamma response of valve group (rad)
c     ar    = alpha response of valve group (radians)
c     f     = system base frequency in hertz
c     amin = alpha minimum limit (rad)
c     amax = alpha maximum limit  (rad)
c     gmin = gamma minimum order (rad)
c
c   output
c     ao   = alpha order (rad) to valves
c
      common /s1/time,delt,ich,print,fintim
      common /s2/stor(5000),nexc
      common /s4/var(100),con(100),pgb(25)
      if (time.ge.delt) go to 10
c   initialization
      do 5 i=1,6
      n=nexc+i+8
      stor(n)=gmin
    5 continue
      stor(nexc+1)=0.0
      stor(nexc+2)=0.0
      stor(nexc+4)=0.0833/f
      stor(nexc+5)=stor(nexc+4)
      stor(nexc+6)=da
      stor(nexc+7)=gmin
      stor(nexc+8)=gmin
      stor(nexc+15)=da
      if (amax.lt.3.0) stor(nexc+21)=0.157
      stor(nexc+36)=0.0
   10 continue
c  to set up super increment
      if (time.lt.stor(nexc+5)) go to 100
      stor(nexc+5)=time+stor(nexc+4)
c   to load up gamma min shifting it one stage down
      glow=stor(nexc+8)
      a1=g-stor(nexc+7)
      if (abs(a1).lt.1.0e-04) go to 20
      do 11 i=1,5
      j=7-i
      n=nexc+j+8
      m=n-1
      stor(n)=stor(m)
   11 continue
      stor(m)=g
c   to determine lowest gamma over past cycle
```

```
  130 h2=dt5*h1*3600.0*var(32)
      h3=stor(nexc+6)+h2+stor(nexc+3)
      stor(nexc+3)=h2
c modification done by t.shome -- vco exact transfer function.
      if (h3.gt.amax) h3=amax
      if (h3.lt.amin) h3=amin
      ao=h3
      stor(nexc+6)=h3
      nexc=nexc+36
c
      return
      end
      subroutine polc12(co,cd,cm,dv,amin,amax,gr1,gr2,x,cx,dge,da)
c  subroutine to model pole controls - one per pole
c    current error control amplifier included
c
c    this model contains the non-linear gain function and
c    the arcos lineariser.
c
c  inputs
c      co = dc current ordered in pu (always +ve)
c      cd = dc current response in pu (always +ve)
c      cm = current margin in pu (+ve for inverter, 0 or -ve for rect)
c      dv = per unit incremental dc volts defining current error slope
c    amin = alpha min (eg: 5 deg for rect, 90-110 deg for inv) in rad
c    amax = alpha max (eg: 3.14 max) in rad
c     gr1 = integral gain kr1   degrees/amp-sec  (+ve)
c     gr2 = proportional gain kr2    sec
c       x = slope of non-linear portion as a fraction of gain (<1.0)
c      cx = per unit width of non-linear portion
c
c  outputs
     dge = delta gamma error (rad)
      da = desired alpha (rad)
c
      common /s1/time,delt,ich,print,fintim
      common /s2/stor(5000),nexc
c
c  to check if limits have changed
      al1=amin-stor(nexc+7)
      if (abs(al1).lt.1.0e-03) go to 21
      am1=cos(amin)
      stor(nexc+8)=1.5708*(1.0-am1)
   21 stor(nexc+7)=amin
      al2=amax-stor(nexc+9)
      if (abs(al2).lt.1.0e-03) go to 22
      am2=cos(amax)
      stor(nexc+10)=1.5708*(1.0-am2)
   22 stor(nexc+9)=amax
      aminz=stor(nexc+8)
      amaxz=stor(nexc+10)
c
c  assume steady state initialization not required
      if (time.ge.delt) go to 5
      stor(nexc+2)=aminz
      stor(nexc+1)=aminz
c   to approximate slope of current error control
c   assume gamma = 18 deg, xc = 0.2 pu.
      stor(nexc+4)=0.0
      stor(nexc+5)=0.0
      stor(nexc+6)=cx*(1.0-x)
      if (cm.le.0.0) go to 5
      a1=dv
      if (dv.lt.0.0) a1=0.0
      if (dv.gt.0.2) a1=0.2
      stor(nexc+4)=2.1*a1/cm
```

```
c ** current control
  5 a1=cd-co+cm
c  non-linear gain function,  slope = 1/x,  width =+/- cx
    if (abs(a1).gt.cx) go to 2
    a1=a1*x
    go to 4
  2 if (a1.lt.0.0) go to 3
    a1=a1-stor(nexc+6)
    go to 4
  3 a1=a1+stor(nexc+6)
  4 a5=a1*31.42*gr1
c  current summation and prop-int controller
    a6=stor(nexc+2)+0.5*delt*(a5+stor(nexc+3))
    a7=a5*gr2
    if (a6.lt.aminz) a6=aminz
    if (a6.gt.amaxz) a6=amaxz
    a6a=stor(nexc+2)
    stor(nexc+2)=a6
    stor(nexc+3)=a5
    stor(nexc+1)=a6a+a7
    dax=stor(nexc+1)
    if (dax.lt.aminz) dax=aminz
    if (dax.gt.amaxz) dax=amaxz
c  arcos function
    dac=time-stor(nexc+11)
c   if (dac.lt.0.0) go to 41
    day=1.0-0.63662*dax
    daz=arcos(day)
    stor(nexc+12)=daz
    stor(nexc+11)=time+0.0012
 41 da=stor(nexc+12)
c  current error control
c      dge time constant is 49.0 ms. ---t.shome.
    cdo=cd-co
    if (cdo.lt.-0.2) cdo=-0.2
      dcd=20.0*(cdo-stor(nexc+5))
    a1=stor(nexc+5)+dcd*delt
    if (a1.gt.0.0) a1=0.0
    dge=stor(nexc+4)*stor(nexc+5)
    stor(nexc+5)=a1
    nexc=nexc+12
    return
    end
    function arcos(x)
    x1=x
    if (x.ge.0.99999) x1=0.99999
    if (x.le.-0.99999) x1=-0.99999
    a1=sqrt(1.0-x1*x1)
    a2=x1/a1
    a3=atan(a2)
    arcos=1.5707963-a3
    return
    end
    subroutine vg2c18(da,dge,cd,g,f,amin,amax,gmin,ao)
c   subroutine to model valve group controls - 1 for each vg
c  to be used in conjunction with pol2c5 pole controller
c  ***********************************************************
c*************************************************************
c           note:  the information contained in this
c                  subroutine is developed by manufacturers
c                  and is considered their property and
                   is not to be disclosed to anyone except
                   employees of manitoba hydro or their
c                  duly authorised representatives.
c  ***********************************************************
c*************************************************************
```

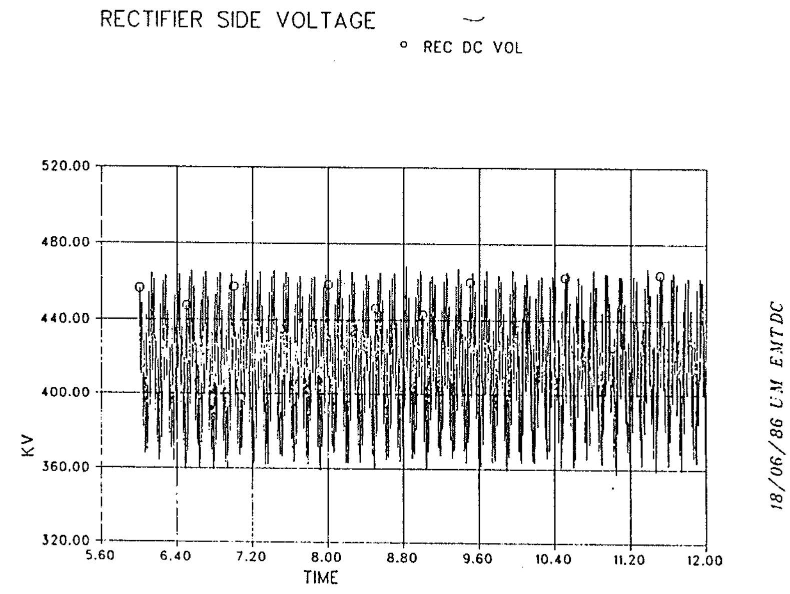
```
c        pi contreoller has 0.05 and 5.00 gain.
c    inputs
c      da   = desired alpha from pole control (rad)
c      dge  = gamma error from pole control (rad)
       cd   = dc current (always +ve) in per unit
       g    = gamma response of valve group (rad)
c      f    = system base frequency in hertz
c      amin = alpha minimum limit (rad)  assume rectifier lt 0.35 radians
c      amax = alpha maximum limit  (rad)
c      gmin = gamma minimum order  (rad)
c
c    output
c      ao  = alpha order (rad) to valves
c
       common /s1/time,delt,ich,print,fintim
       common /s2/stor(5000),nexc
       if (time.ge.delt) go to 10
c    initialization
       do 5 i=1,6
       n=nexc+i+8
       stor(n)=gmin
     5 continue
       stor(nexc+1)=0.0
       stor(nexc+2)=0.0
       stor(nexc+3)=cd
       stor(nexc+4)=0.0833/f
       stor(nexc+5)=stor(nexc+4)
       stor(nexc+6)=0.0
       stor(nexc+7)=gmin
       stor(nexc+8)=gmin
       stor(nexc+15)=200.0*delt
       stor(nexc+16)=da
       if (amin.lt.0.35) stor(nexc+16)=amax
       stor(nexc+18)=da
    10 continue
c   to set up super increment
       if (time.lt.stor(nexc+5)) go to 100
       stor(nexc+5)=time+stor(nexc+4)
c    to load up gamma min shifting it one stage down
       glow=stor(nexc+8)
       a1=g-stor(nexc+7)
       if (abs(a1).lt.1.0e-04) go to 20
       do 11 i=1,5
       j=7-i
       n=nexc+j+8
       m=n-1
       stor(n)=stor(m)
    11 continue
       stor(m)=g
c    to determine lowest gamma over past cycle
       glow=g
       do 12 i=1,6
       n=nexc+8+i
       if (stor(n).ge.glow) go to 12
       glow=stor(n)
    12 continue
       stor(nexc+7)=g
    20 continue
c   to recognise rectifier and jump gamma min control
c    to recognise that a rectifier is being processed,
c    assume alpha min is less than 20 degrees
       if (amin.gt.0.35) go to 99
       stor(nexc+6)=0.0
c   detection of gamma spread over past cycle
    99 ghigh=g
       do 14 i=1,6
```

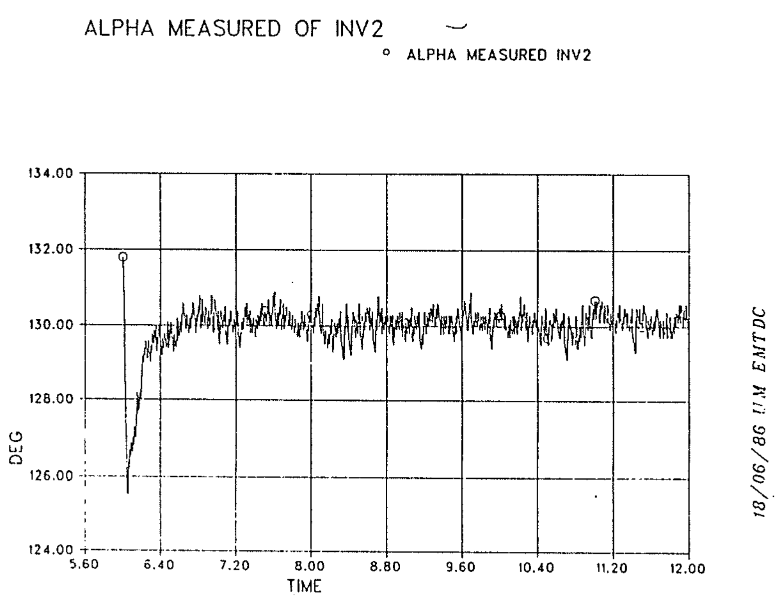
```
         n=nexc+8+i
         if (stor(n).lt.ghigh) go to 14
         ghigh=stor(n)
   14 continue
c  to determine the spread of gamma measured
         gs=ghigh-glow-0.0873
         if (gs.lt.-0.017) gs=-0.017
         if (gs.gt.0.17) gs=0.17
         stor(nexc+17)=stor(nexc+17)+stor(nexc+4)*(gs-stor(nexc+17))*10.0
         gst=stor(nexc+17)
         if (gst.gt.0.122) gst=0.122
         if (gst.lt.0.0) gst=0.0
c  level detector for minimum gamma
         di= cd-stor(nexc+3)
         g1=gmin-glow-0.035
         if (g1.lt.0.0) go to 25
         a1=abs(glow-stor(nexc+8))
         dg2=0.0
         if (a1.gt.1.0e-05) dg2=g1+0.035
         go to 26
   25 dg2=-0.002
         if (glow.lt.gmin) dg2=0.0
c  gamma increase on comm fail
   26 if (glow.lt.1.0e-04) dg2=0.18
         stor(nexc+6)=stor(nexc+6)+dg2
         if (stor(nexc+6).lt.0.0) stor(nexc+6)=0.0
         if (stor(nexc+6).gt.1.0) stor(nexc+6)=1.0
         if (time.gt.0.1) go to 27
         stor(nexc+6)=0.0
   27 stor(nexc+8)=glow
c
c   to include the effects of di/dt to advance gamma
         stor(nexc+3)=stor(nexc+3)+di*stor(nexc+4)*62.5
         dl=0.4
         dj=di-dl
         dk=0.0
         if (amin.lt.1.57) go to 29
         if (dj.gt.0.4) dk=di
   29 if (dge.lt.-0.87) dge=-0.87
c   gamma control amplifier
         g2=gmin-glow-dge+dk*1.25+gst
         a1=-g2*5.00*3.14
         a3=stor(nexc+16)+a1*stor(nexc+4)
         if (a3.gt.amax) a3=amax
         if (a3.lt.amin) a3=amin
         stor(nexc+16)=a3
         a2=0.0100*a1+a3
         if (a2.gt.amax) a2=amax
         if (a2.lt.amin) a2=amin
         stor(nexc+18)=a2
  100 continue
c  to determine which control defines alpha
         i=nexc+1
         a2=da-stor(i)
         if (abs(a2).lt.stor(nexc+15)) go to 40
         a3=stor(nexc+15)
         if (a2.lt.0.0) a3=-a3
         stor(i)=stor(i)+a3
         go to 45
   40 stor(i)=da
   45 if (stor(i).gt.amax) stor(i)=amax
         if (stor(i).lt.amin) stor(i)=amin
         ao=amin1(stor(i),stor(nexc+18))
         nexc=nexc+18
         return
         end
```

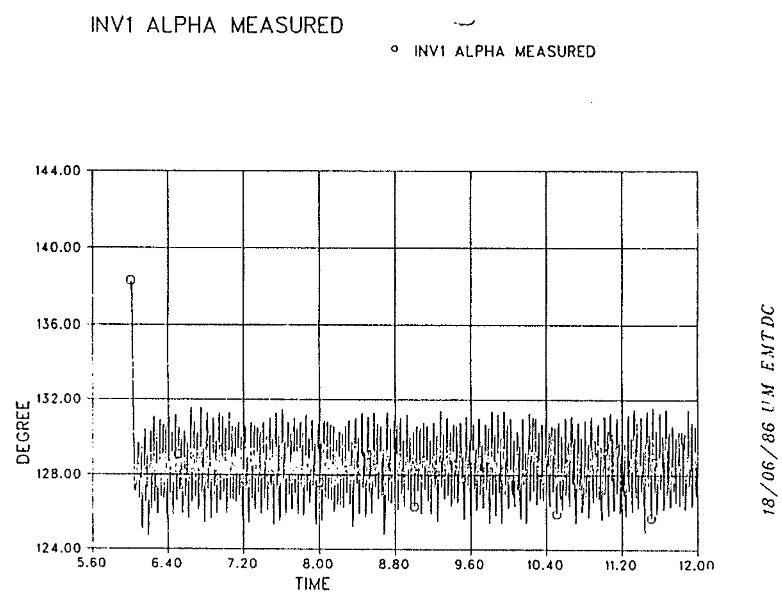
Appendix C

This section contains simulation results of the four tap settings of inverter 1 and inverter 2 transformer. Note only one case of the above four is unstable and demonstrate, as observed in the Nelson River System, 6hz oscillation.

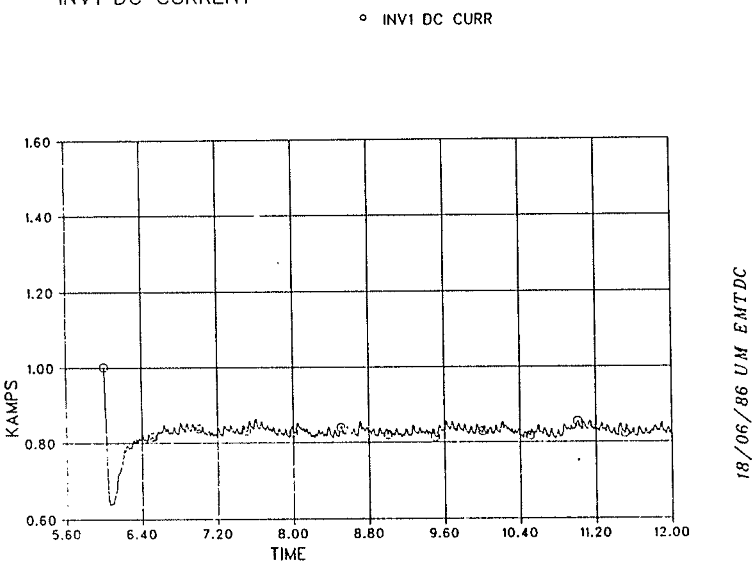
```
File DATA2 printed on Wed Jun 18 13:07:13 1986
------------------------------------------------------------------------
    SIMPLE DC-AC SYSTEM /
0.00005 6.00 .0050 /THIS IS FROM FIXIT DIR
  / NO OF SUB SYSTEMS
  / NO OF NODE IN SS1
0 / INITIAL VOLTAGE
1 4 0.1 /SMALL RES
2 5 0.1 /SMALL RES
3 6 0.1 /SMALL RES
999 /
4 0.1 /SOURCE RESIST
5  0.1/
6  0.1 /
999 /
999 /
6 / SUB SYSTEM 2 IS HERE
0 /
1 3  0.0 1.72 /  LINE INDUCTANCE OF 2 H ASSUMED
3 5  0.0 0.55 / SMOOTHING REACTOR OF 1H FOR POLE1 INV1
3 6  0.0 0.37 / SMOOTHING REACTOR OF .75 FOR POLE1 INV2
3  0  0.0 0.0 .5 /.5 UF LINE TO GND.
5 2 0.0 0.55/
6 4 0.0 .37/
-5 0 4.42 0.195 1.0 /2X6th filter bpl
-5 0 5.50 0.122 0.4 /2X12th filter bpl
999 /
1 0.1 /SOURCE RES OF RECTIFIER
2 .1 /VALVE GROUP IS HERE FOR INV1 POLE1
4 .1 / VALVE GROUP IS HERE FOR INV2 POLE1
999 /
999 /
999 /
-10. 10./ PRINT PLOT LIMITS
20 / NO OF CHANNELS
186.6 0.020 2.0 600.0 0.02  1.1500
1.00  323.0 262.0 127.0 127.0 0.2 0.2 1.00 1.00 0.1 0.1
0.1 0.1 0.15 6.0 0.50 0.0150  0.020 0.020  2.00 0.5
3.14 1.0 1.0 0.00  0.20 2.80/ VAR(28) =POL1C7 INTEGRAL VAR(33)=VG1C3G ALPHA CON GAIN -DDA
999 /
```



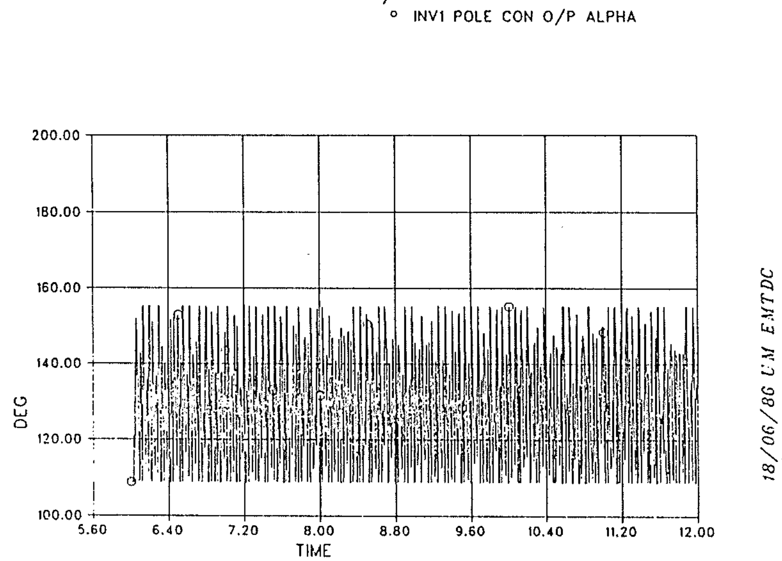




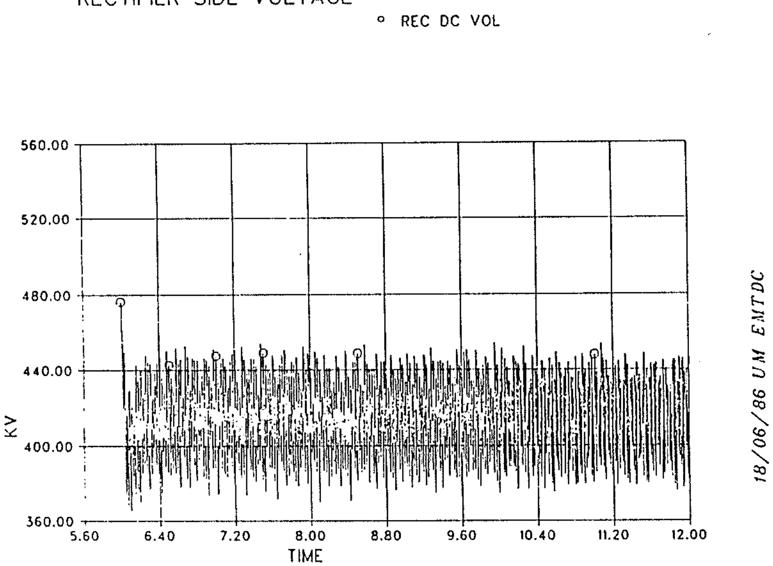
INV1 DC CURRENT



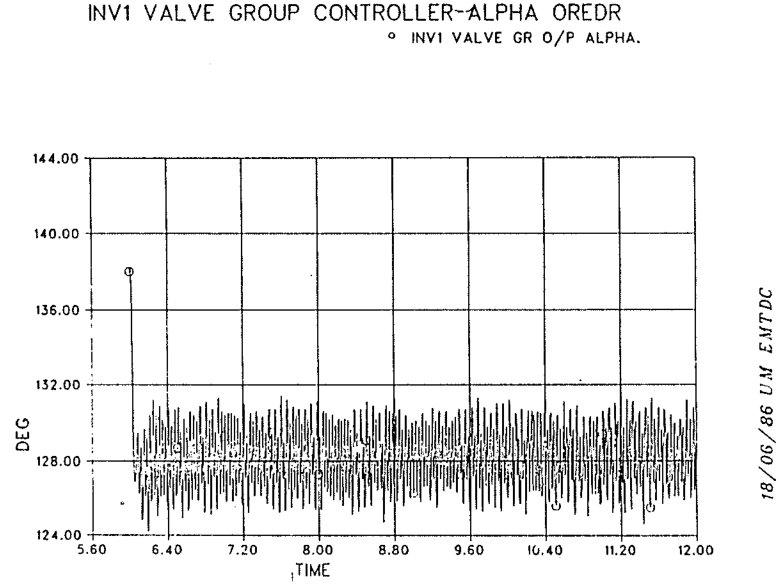
INV1 POLE CONTROLLER O/P ALPHA ORDER.

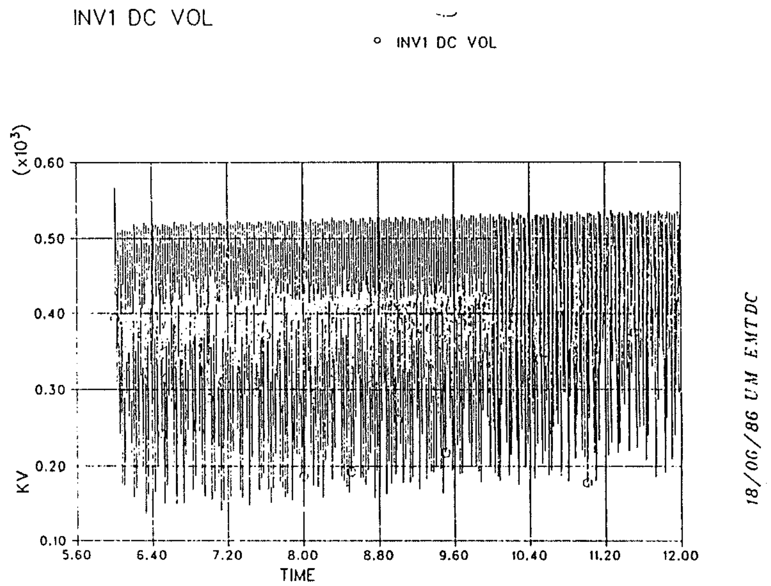


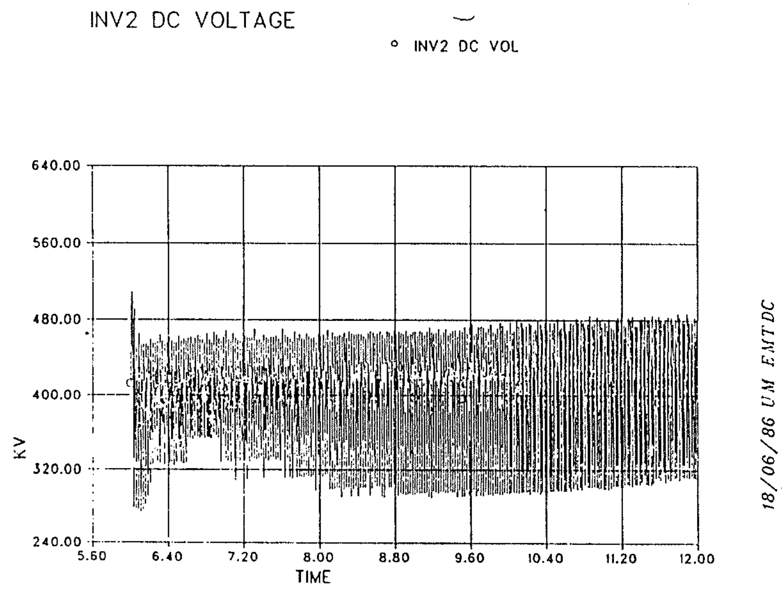
RECTIFIER SIDE VOLTAGE

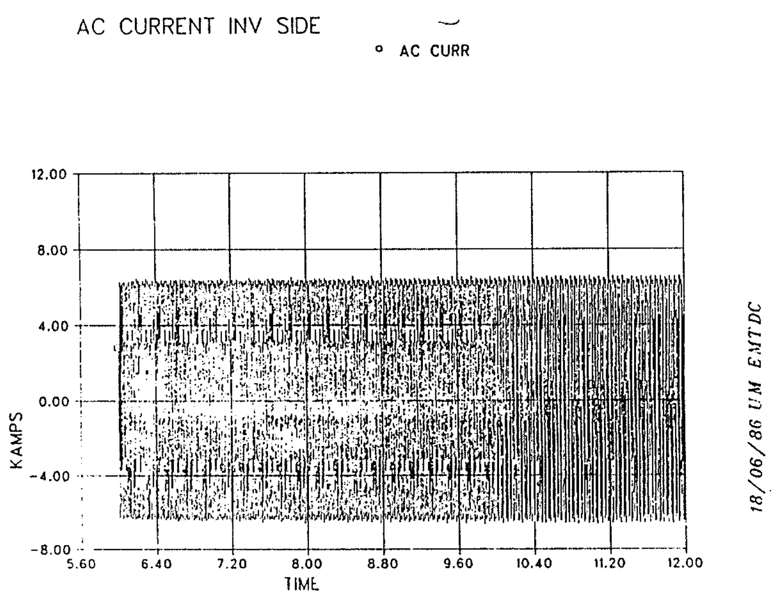


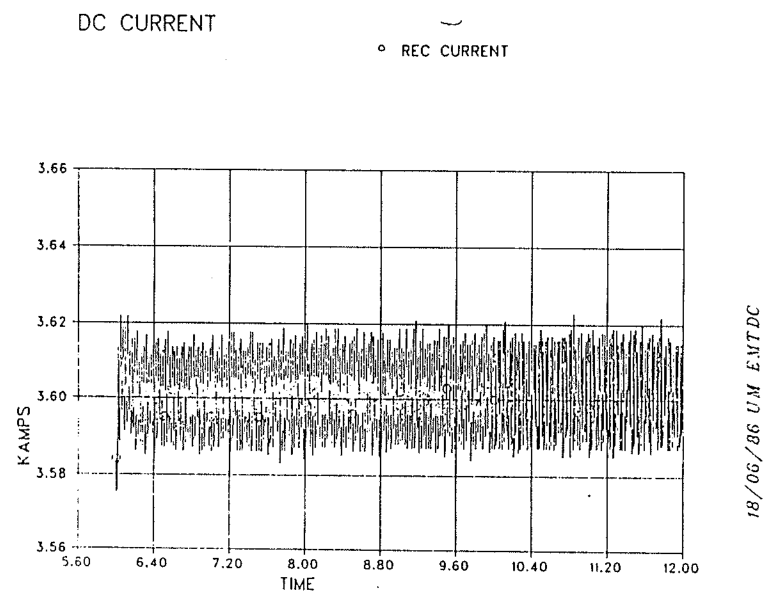
INV1 VALVE GROUP CONTROLLER-ALPHA OREDR



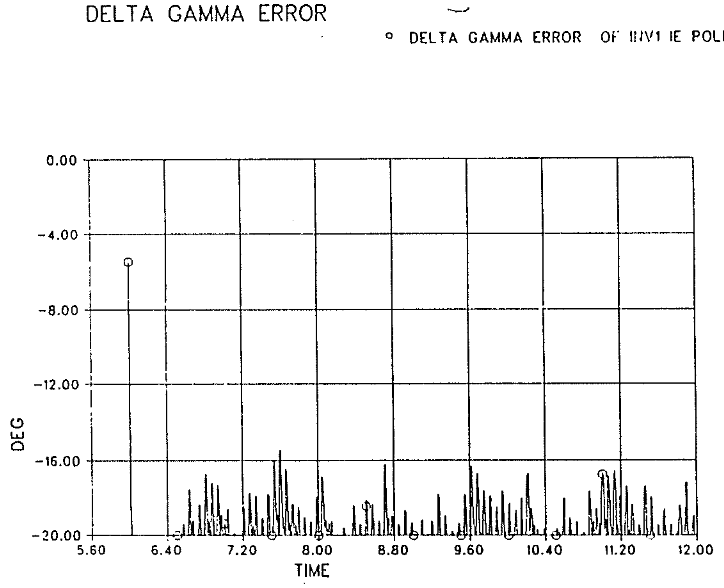

INV1 DC VOL
INV1 DC VOL
(x10^3)
KV
TIME
18/06/86 UM EMTDC


INV2 DC VOLTAGE
INV2 DC VOL
KV
TIME
18/06/86 UM EMTDC


AC CURRENT INV SIDE
AC CURR
KAMPS
TIME
18/06/86 UM EMTDC

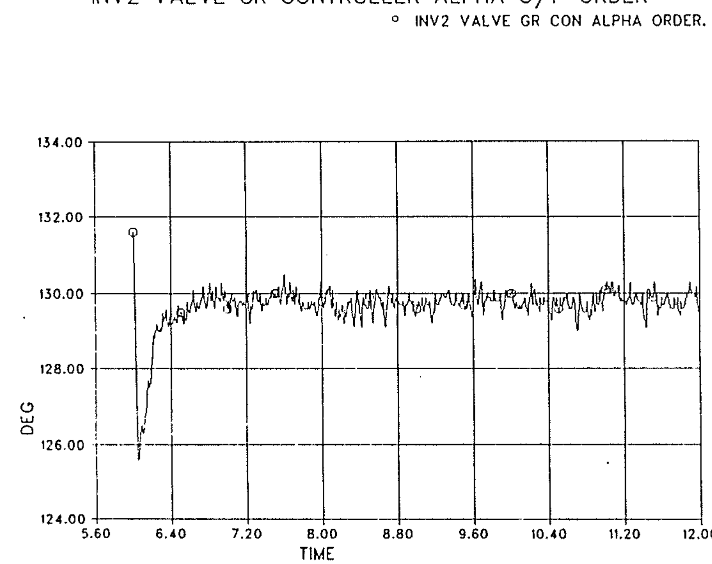

DC CURRENT
REC CURRENT
KAMPS
TIME
18/06/86 UM EMTDC

DELTA GAMMA ERROR



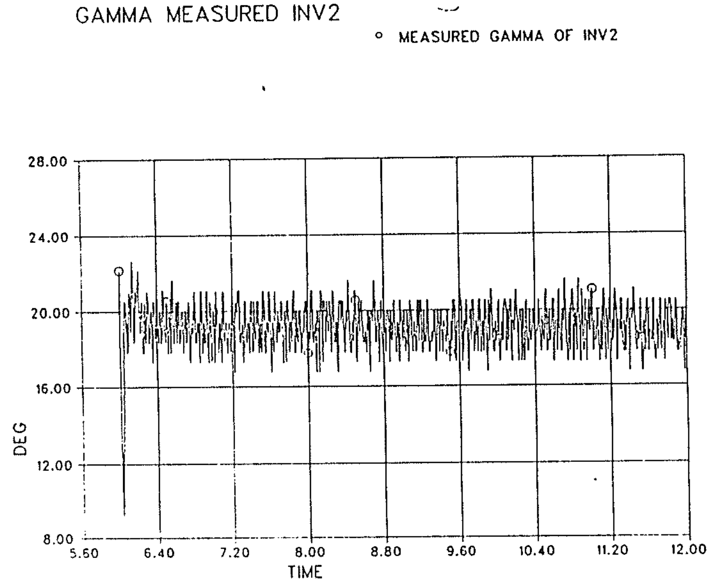
18/06/86 UM EMTDC

INV2 VALVE GR CONTROLLER ALPHA O/P ORDER



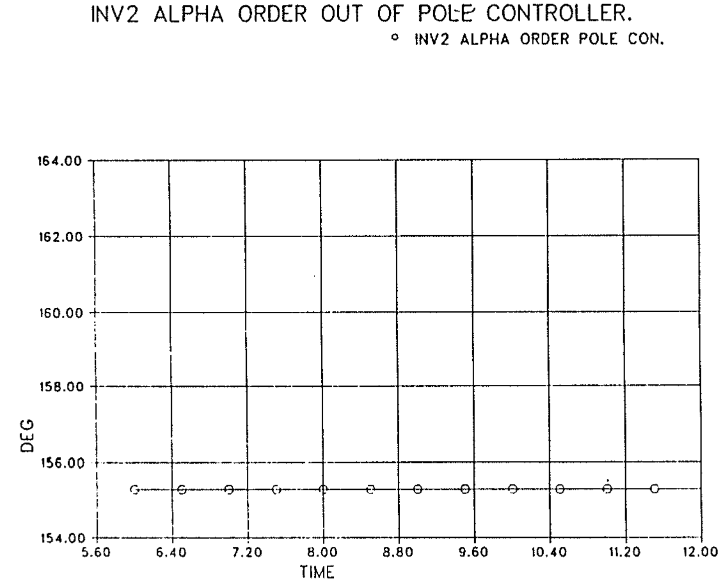
18/06/86 UM EMTDC

GAMMA MEASURED INV2



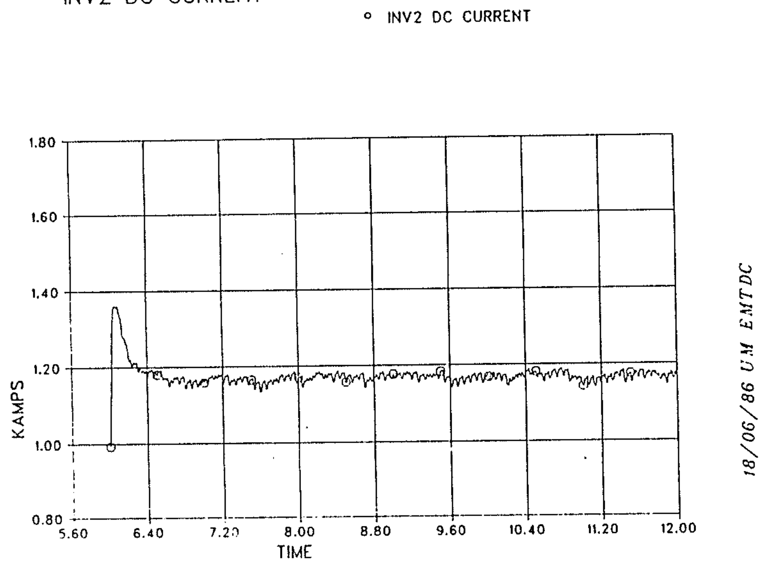
18/06/86 UM EMTDC

INV2 ALPHA ORDER OUT OF POLE CONTROLLER.

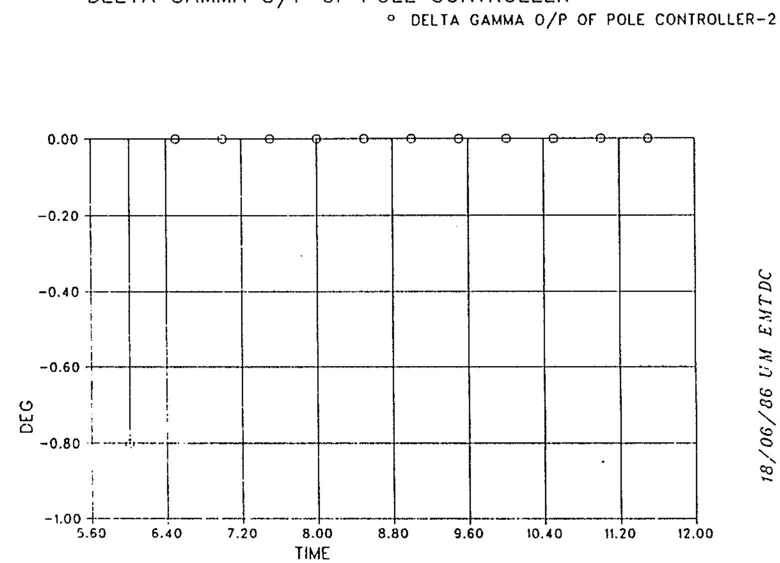


18/06/86 UM EMTDC

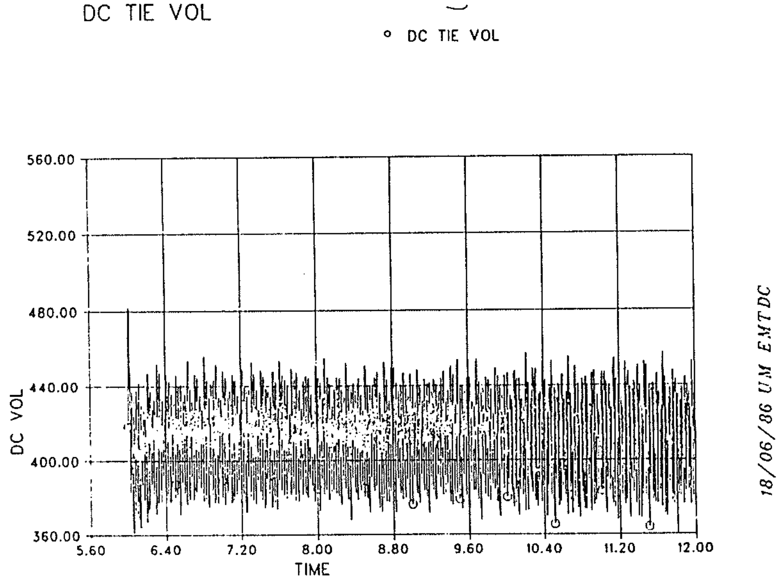
INV2 DC CURRENT



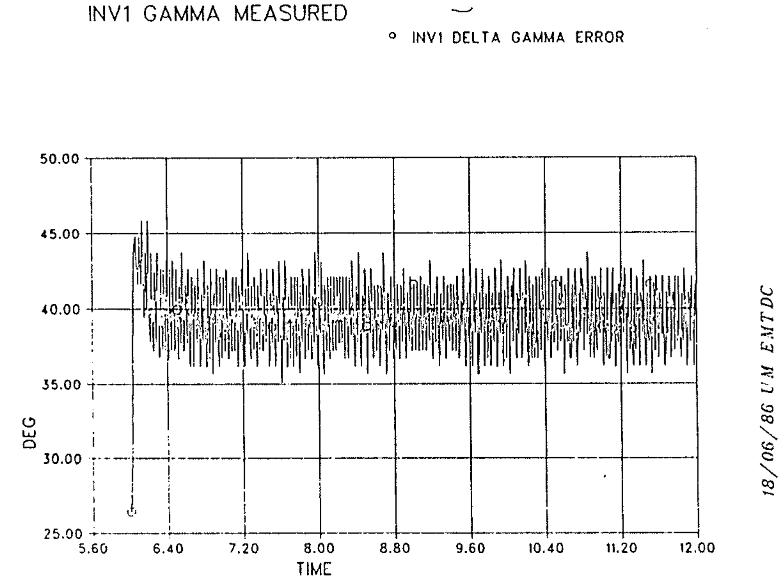
DELTA GAMMA O/P OF POLE CONTROLLER



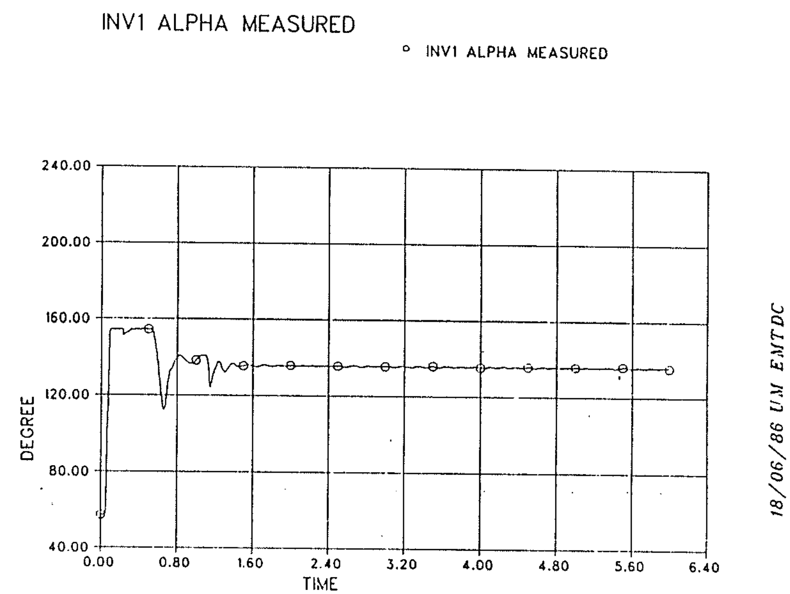
DC TIE VOL

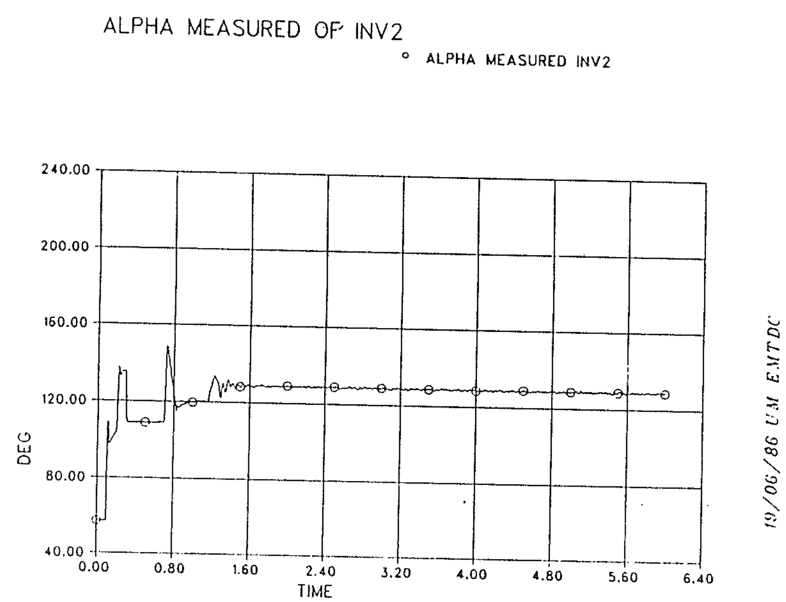


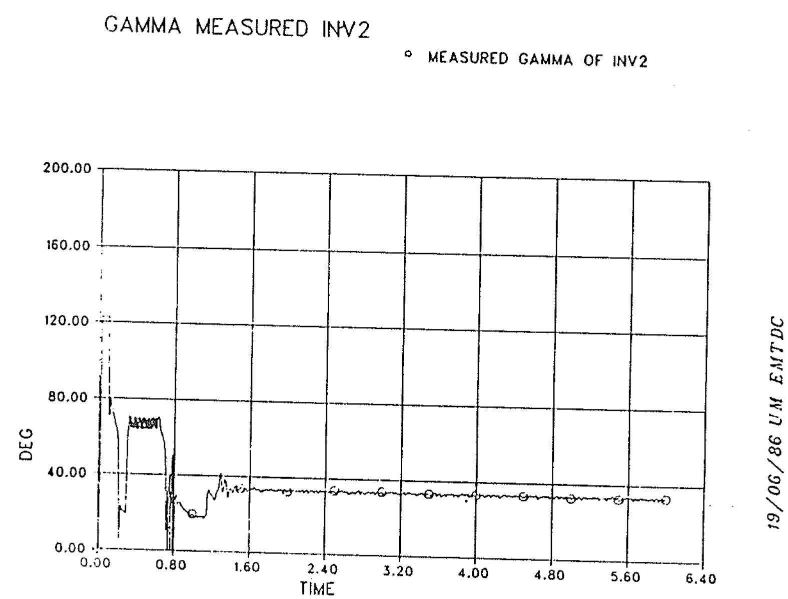
INV1 GAMMA MEASURED

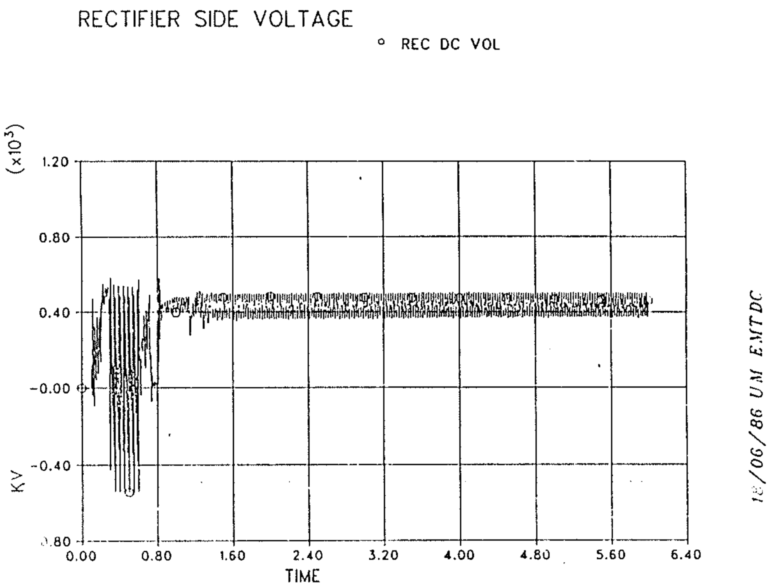


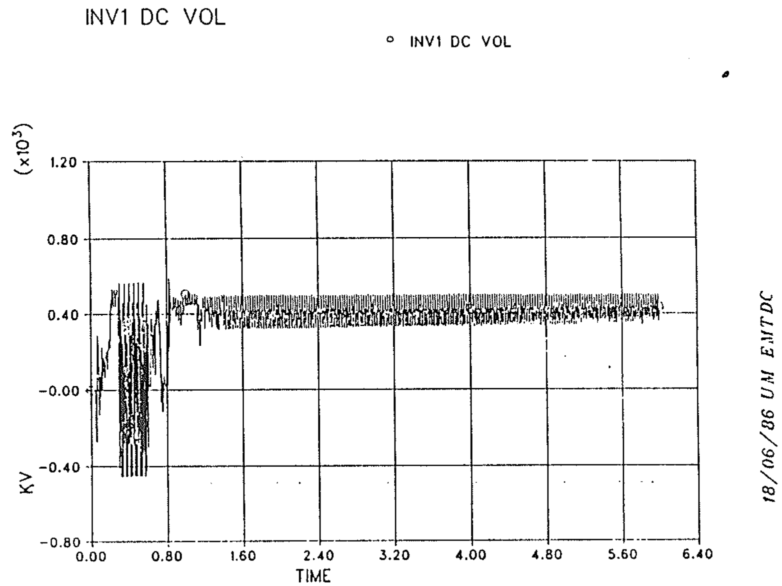
```
File DATA2 printed on Wed Jun 18 21:17:27 1986
--------------------------------------------------------------------------------
    SIMPLE DC-AC SYSTEM /
0.00005 6.00 .0050 /THIS IS FROM FIXIT DIR
2 / NO OF SUB SYSTEMS
5 / NO OF NODE IN SS1
0 / INITIAL VOLTAGE
1 4 0.1 /SMALL RES
2 5 0.1 /SMALL RES
3 6 0.1 /SMALL RES
999 /
4 0.1 /SOURCE RESIST
5  0.1/
6  0.1 /
999 /
999 /
6 / SUB SYSTEM 2 IS HERE
0 /
1 3  0.0 1.72 /  LINE INDUCTANCE OF 2 H ASSUMED
3 5  0.0 0.55 / SMOOTHING REACTOR OF 1H FOR POLE1 INV1
3 6  0.0 0.37 / SMOOTHING REACTOR OF .75 FOR POLE1 INV2
3  0  0.0 0.0 .5 /.5 UF LINE TO GND.
5 2 0.0 0.55/
6 4 0.0 .37/
-5 0 4.42 0.195 1.0 /2X6th filter bpl
-5 0 5.50 0.122 0.4 /2X12th filter bpl
999 /
1 0.1 /SOURCE RES OF RECTIFIER
2 .1 /VALVE GROUP IS HERE FOR INV1 POLE1
4 .1 / VALVE GROUP IS HERE FOR INV2 POLE1
999 /
999 /
999 /
-10. 10./ PRINT PLOT LIMITS
20 / NO OF CHANNELS
186.6 0.020 2.0 600.0 0.02  1.0000
1.15  323.0 262.0 127.0 127.0 0.2 0.2 1.00 1.00 0.1 0.1
0.1 0.1 0.15 6.0 0.50 0.0150  0.020 0.020  2.00 0.5
3.14 1.0 1.0 0.00  0.20 2.80/ VAR(28) =POL1C7 INTEGRAL VAR(33)=VG1C36 ALPHA CON GAIN
999 /
```

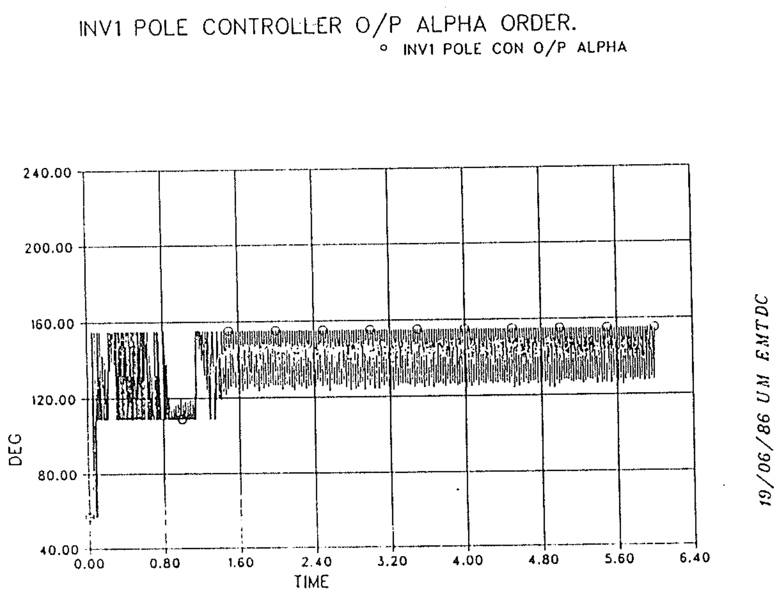


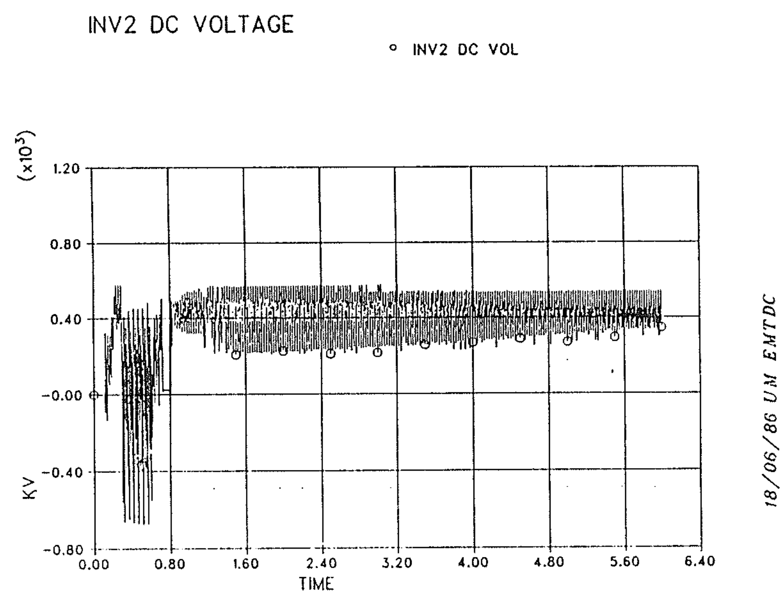


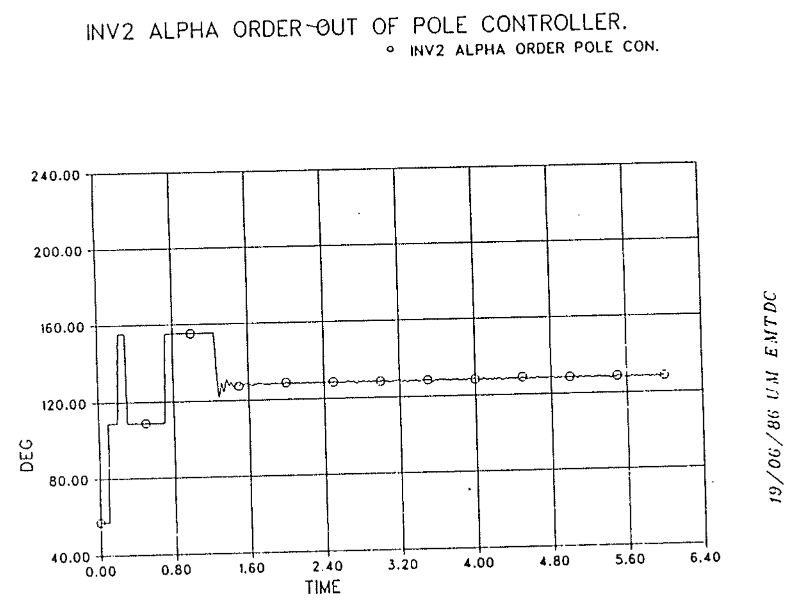



RECTIFIER SIDE VOLTAGE
REC DC VOL
(x10³)
KV
TIME
18/06/86 UM EMTDC

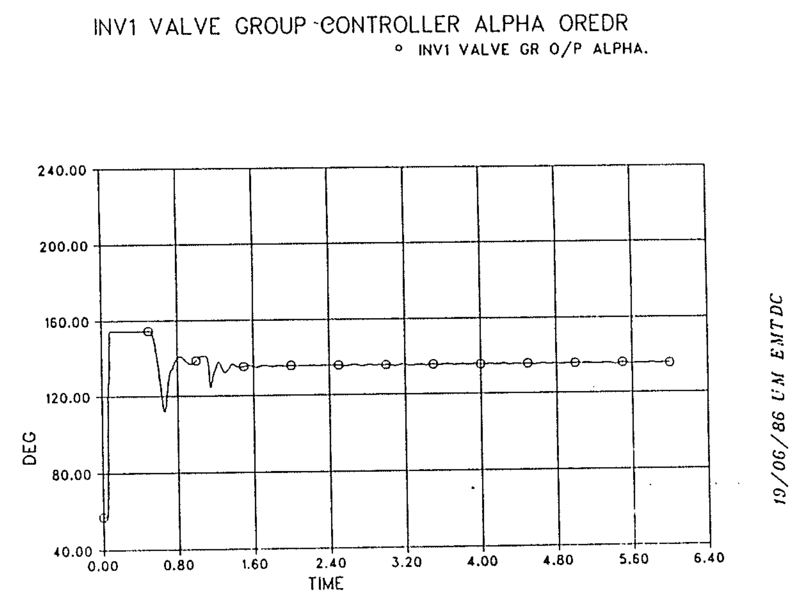

INV1 DC VOL
INV1 DC VOL
(x10³)
KV
TIME
18/06/86 UM EMTDC


INV1 POLE CONTROLLER O/P ALPHA ORDER.
INV1 POLE CON O/P ALPHA
DEG
TIME
19/06/86 UM EMTDC

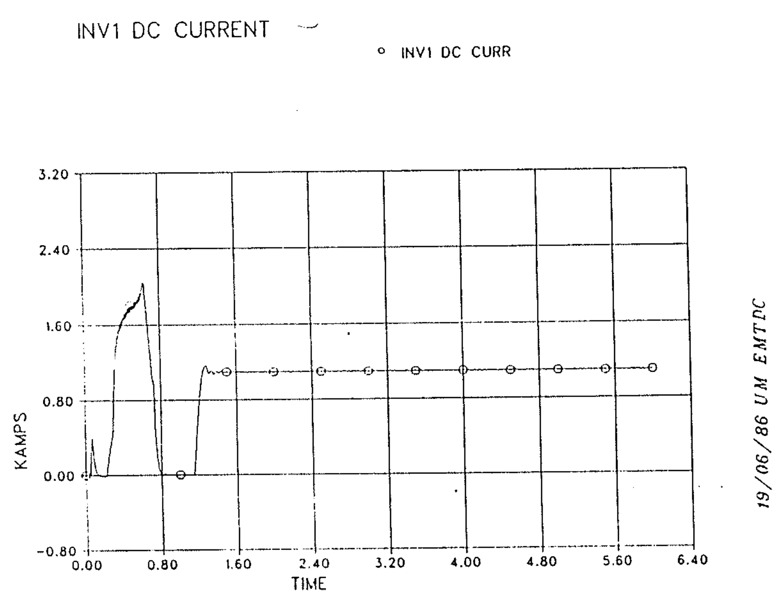

INV2 DC VOLTAGE
INV2 DC VOL
(x10³)
KV
TIME
18/06/86 UM EMTDC



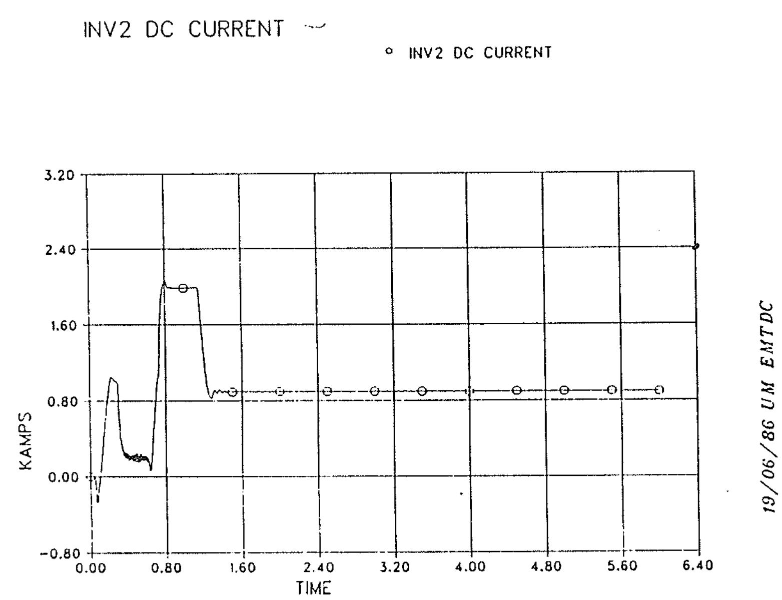
INV2 ALPHA ORDER-OUT OF POLE CONTROLLER.
INV2 ALPHA ORDER POLE CON.
240.00
200.00
160.00
120.00
80.00
40.00
DEG
0.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
TIME
19/06/86 UM EMTDC



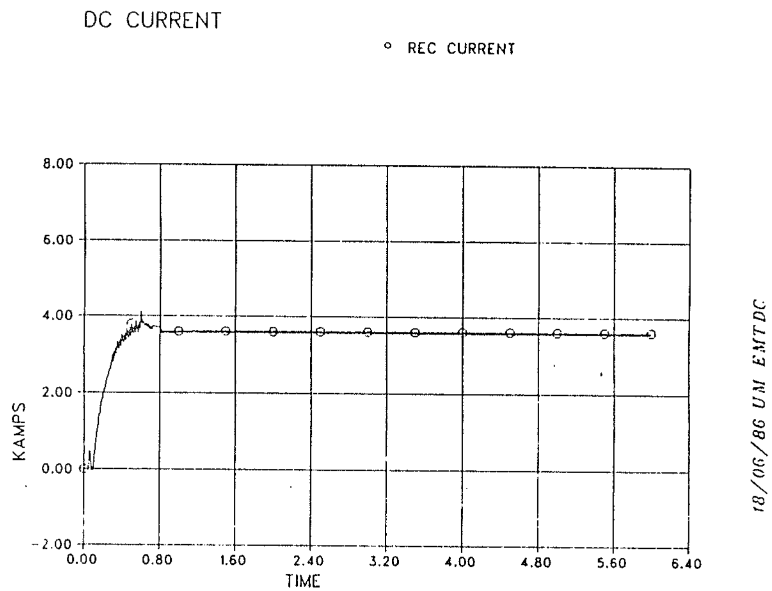
INV1 VALVE GROUP-CONTROLLER ALPHA OREDR
INV1 VALVE GR O/P ALPHA.
240.00
200.00
160.00
120.00
80.00
40.00
DEG
0.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
TIME
19/06/86 UM EMTDC



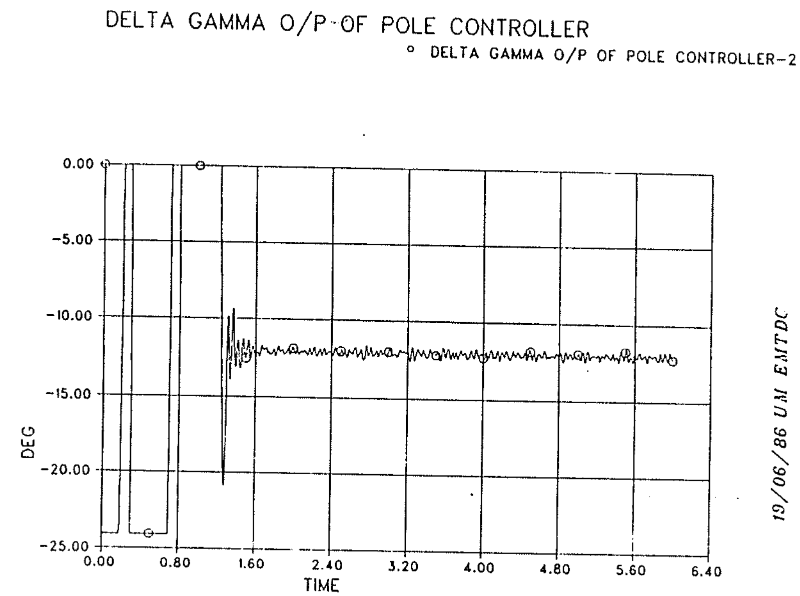
INV1 DC CURRENT
INV1 DC CURR
3.20
2.40
1.60
0.80
0.00
-0.80
KAMPS
0.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
TIME
19/06/86 UM EMTDC



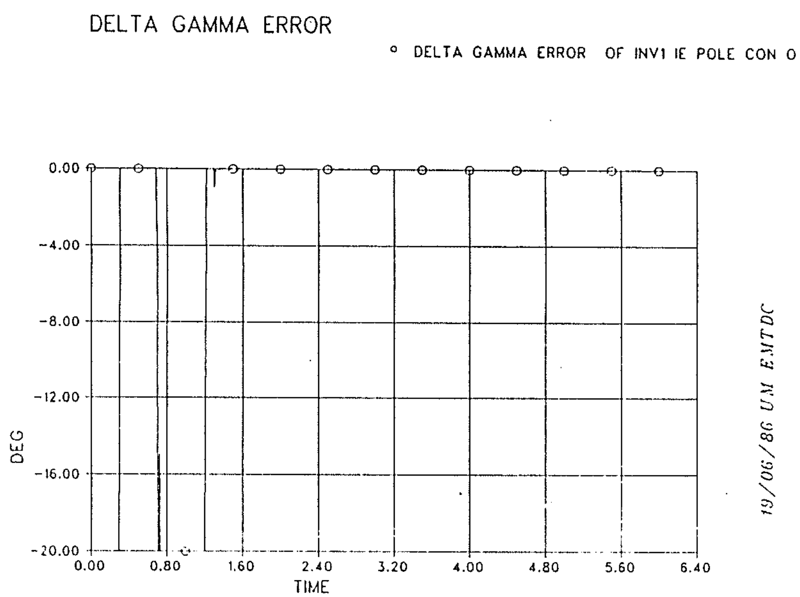
INV2 DC CURRENT
INV2 DC CURRENT
3.20
2.40
1.60
0.80
0.00
-0.80
KAMPS
0.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
TIME
19/06/86 UM EMTDC



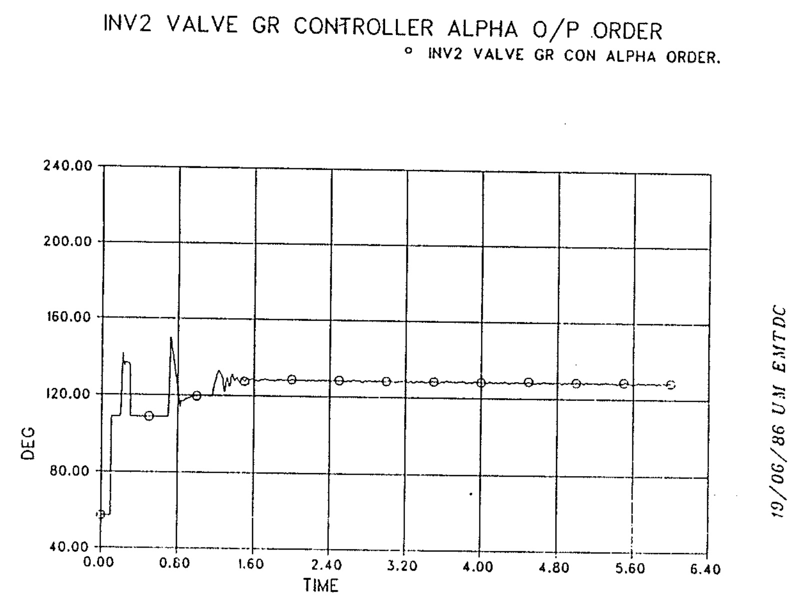
DC CURRENT
REC CURRENT
KAMPS
TIME
18/06/86 UM EMTDC



DELTA GAMMA O/P OF POLE CONTROLLER
DELTA GAMMA O/P OF POLE CONTROLLER-2
DEG
TIME
19/06/86 UM EMTDC

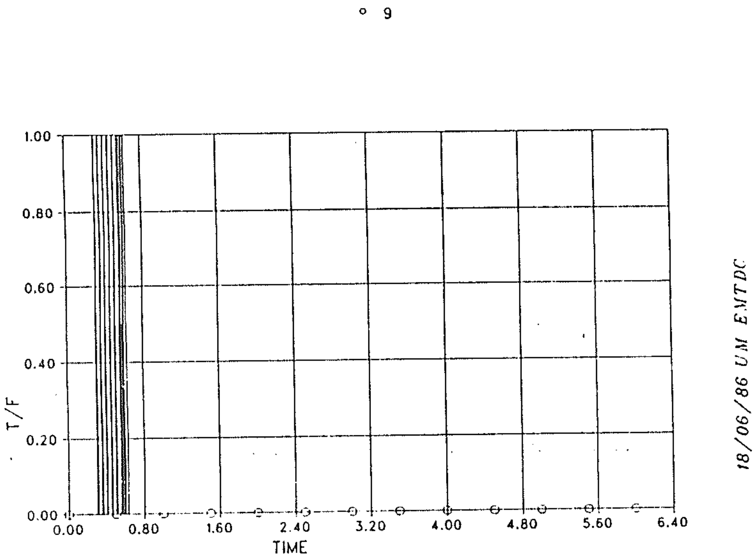


DELTA GAMMA ERROR
DELTA GAMMA ERROR OF INV1 IE POLE CON O
DEG
TIME
19/06/86 UM EMTDC

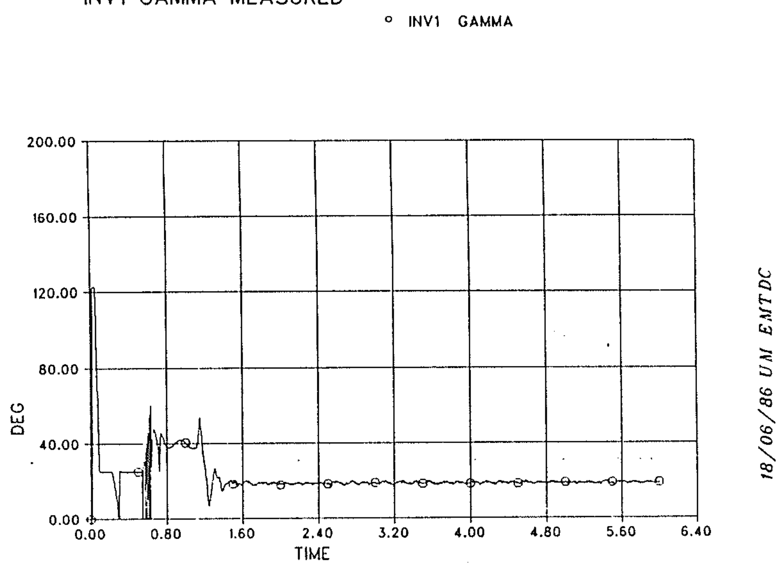


INV2 VALVE GR CONTROLLER ALPHA O/P ORDER
INV2 VALVE GR CON ALPHA ORDER.
DEG
TIME
19/06/86 UM EMTDC

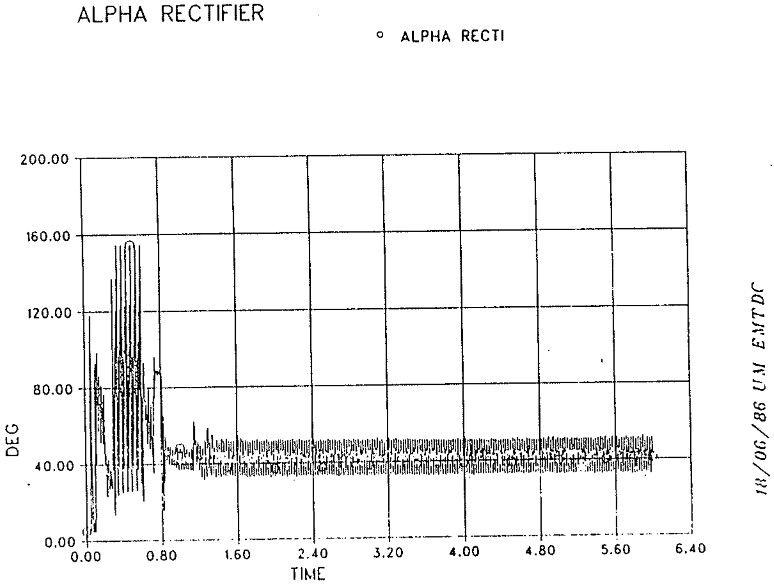
INV1 COMM FAIL



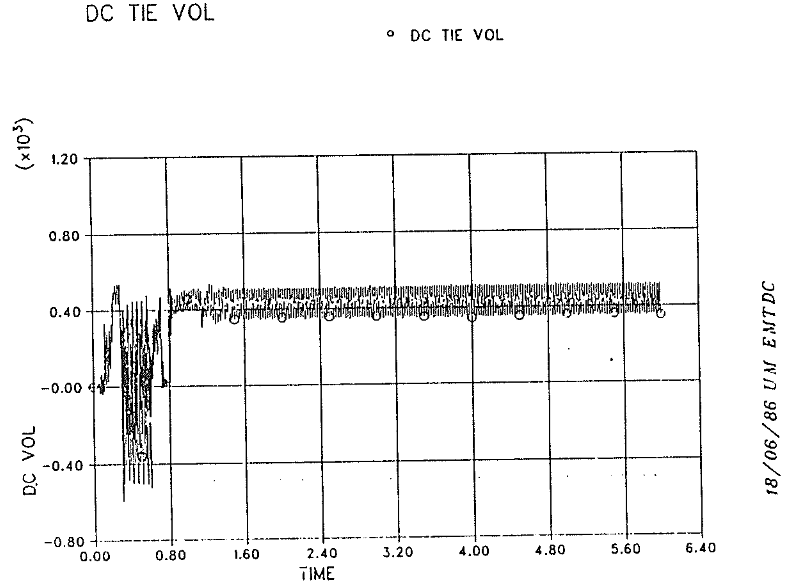
INV1 GAMMA MEASURED



ALPHA RECTIFIER



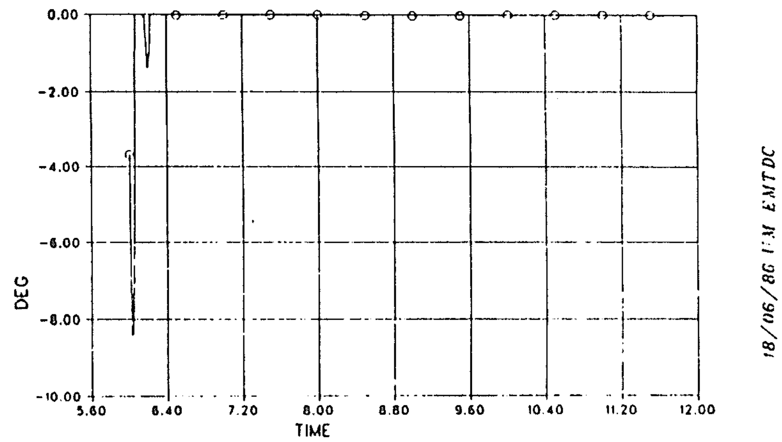
DC TIE VOL



```
File DATA3 printed on Wed Jun 18 19:28:36 1986
------------------------------------------------------------------------------------
    SIMPLE DC-AC SYSTEM /
0.00005 6.00 .0050 /
` / NO OF SUB SYSTEMS
. / NO OF NODE IN SS1
0 / INITIAL VOLTAGE
1 4 0.1 /SMALL RES
2 5 0.1 /SMALL RES
3 6 0.1 /SMALL RES
999 /
4 0.1 /SOURCE RESIST
5  0.1/
6  0.1 /
999 /
999 /
6 / SUB SYSTEM 2 IS HERE
0 /
1 3  0.0 1.72 /  LINE INDUCTANCE OF 2 H ASSUMED
3 5  0.0 0.55 / SMOOTHING REACTOR OF 1H FOR POLE1 INV1
3 6  0.0 0.37 / SMOOTHING REACTOR OF .75 FOR POLE1 INV2
3  0  0.0 0.0 .5 /.5 UF LINE TO GND.
5 2 0.0 0.55/
6 4 0.0 .37/
-5 0 4.42 0.195 1.0 /2X6th filter bpl
-5 0 5.50 0.122 0.4 /2X12th filter bpl
999 /
1 0.1 /SOURCE RES OF RECTIFIER
2 .1 /VALVE GROUP IS HERE FOR INV1 POLE1
4 .1 / VALVE GROUP IS HERE FOR INV2 POLE1
999 /
999 /
999 /
-10. 10./ PRINT PLOT LIMITS
20 / NO OF CHANNELS
186.6 0.020 2.0 600.0 0.02  1.0000
1.05  323.0 262.0 127.0 127.0 0.2 0.2 1.00 1.00 0.1 0.1
0.1 0.1 0.15 6.0 0.50 0.0150  0.020 0.020  2.00 0.5
3.14 1.0 1.0 0.00  0.20 2.00/ VAR(28) =POL1C7 INTEGRAL VAR(33)=VG1C36 ALPHA CON GAIN -DOA
999 /
```

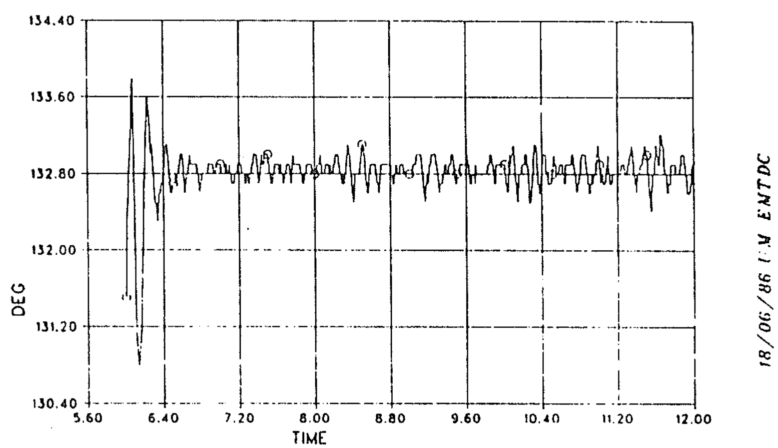
DELTA GAMMA ERROR

° DELTA GAMMA ERROR OF INV1 IE POLE CON O



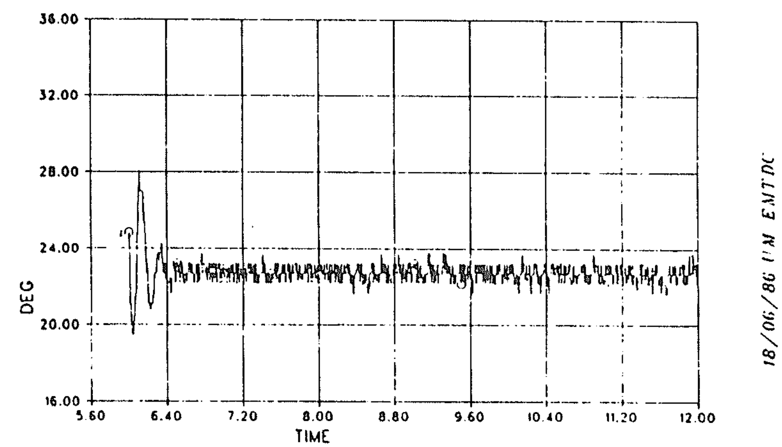
INV2 VALVE GR CONTROLLER ALPHA O/P ORDER

° INV2 VALVE GR CON ALPHA ORDER.

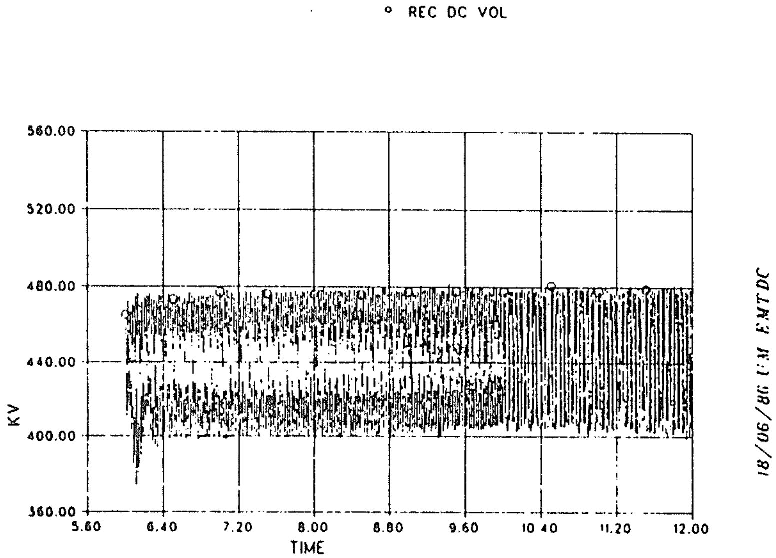


GAMMA MEASURED INV2

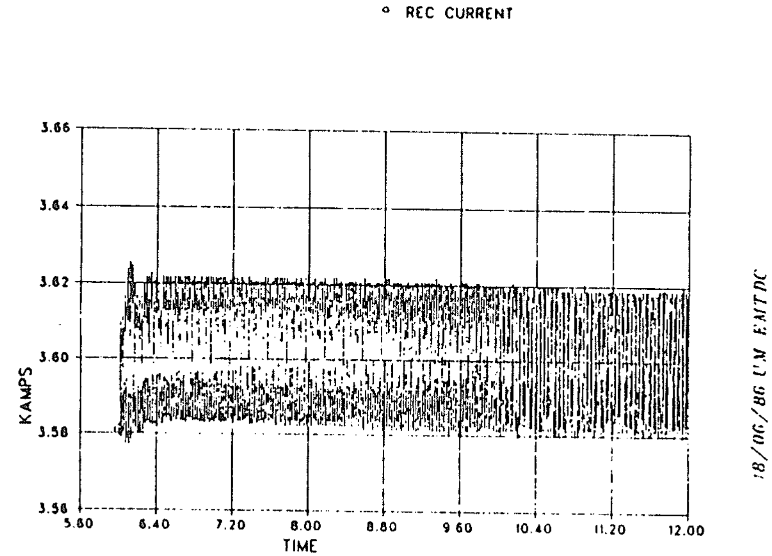
° MEASURED GAMMA OF INV2



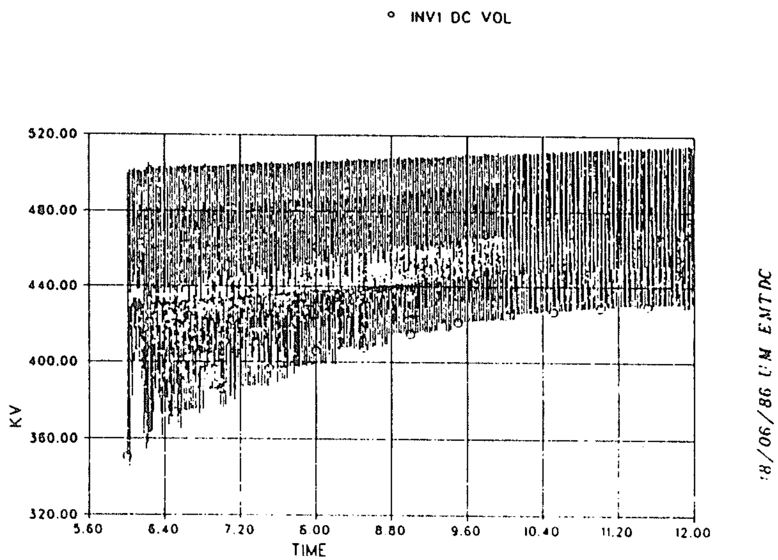
RECTIFIER SIDE VOLTAGE



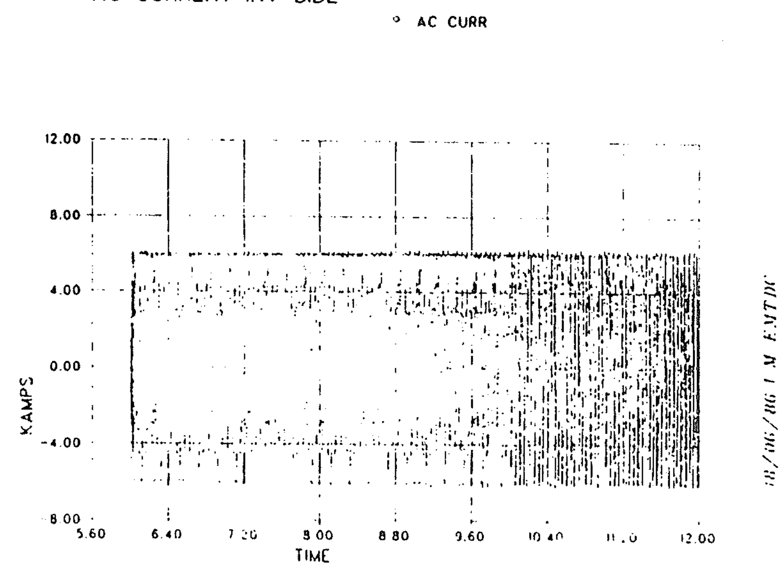
DC CURRENT



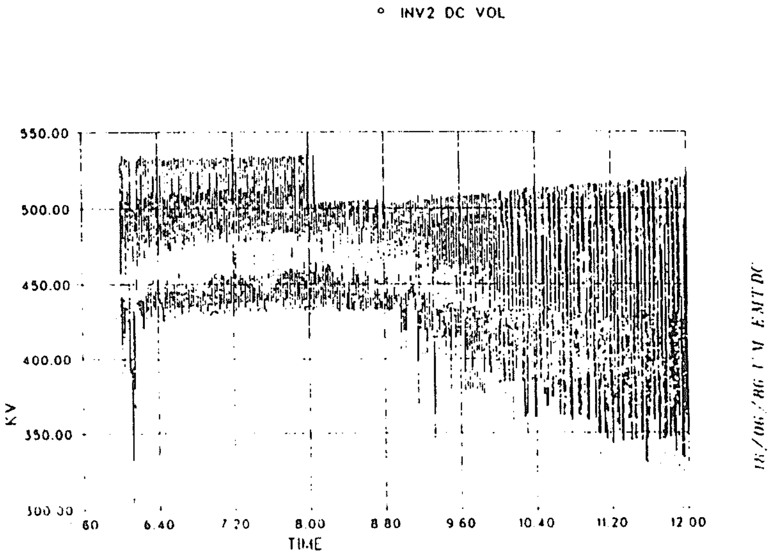
INV1 DC VOL



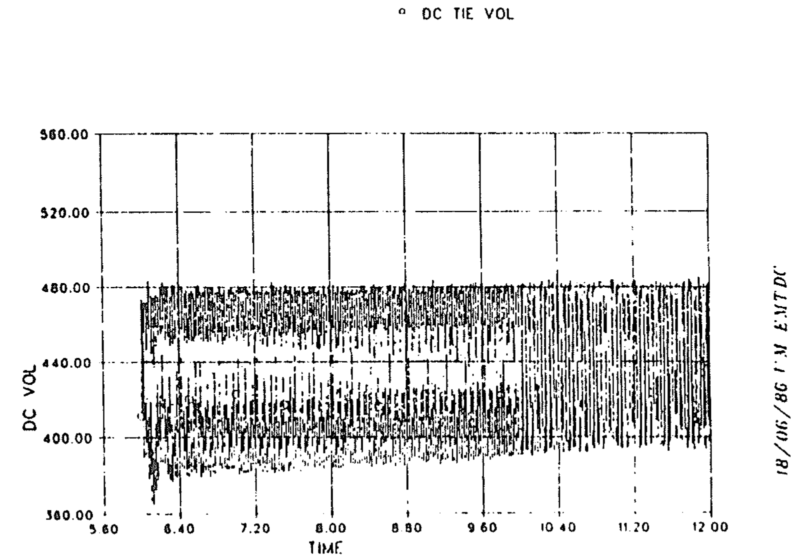
AC CURRENT INV SIDE



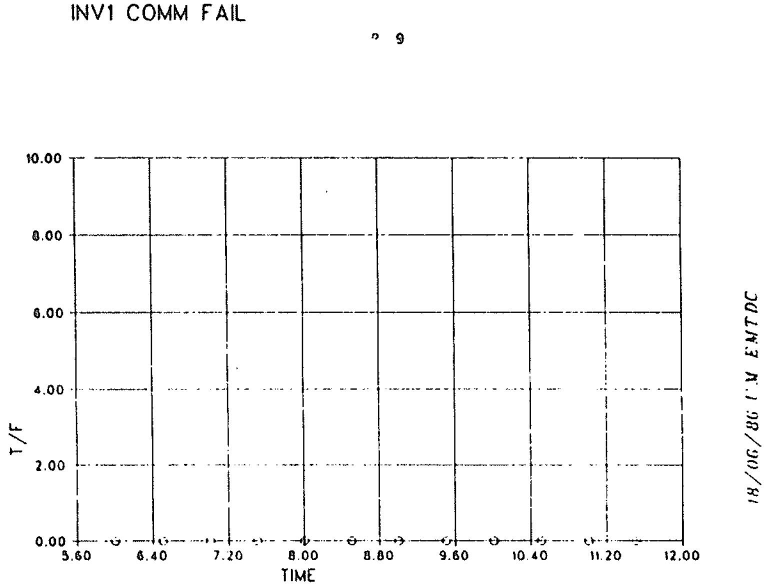
INV2 DC VOLTAGE



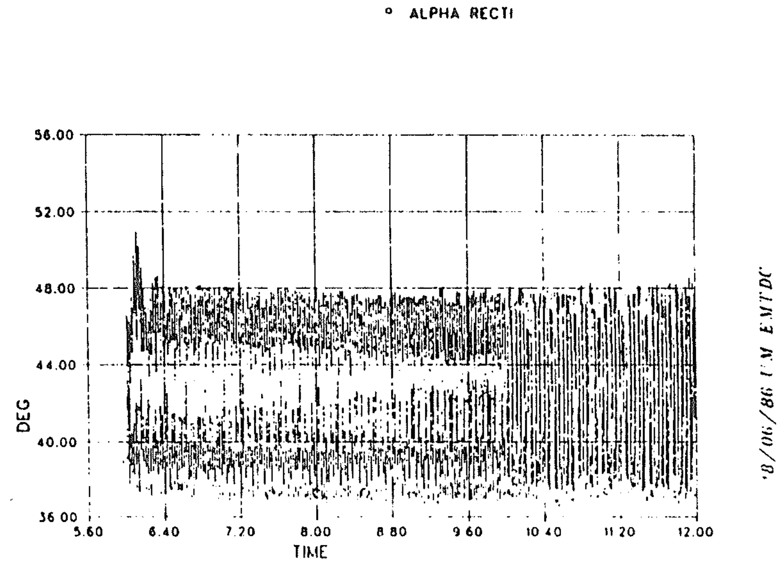
DC TIE VOL



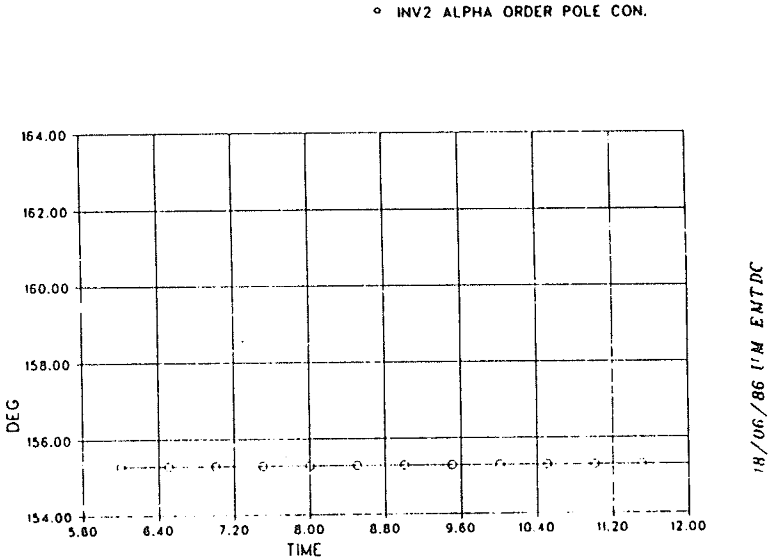
INV1 COMM FAIL



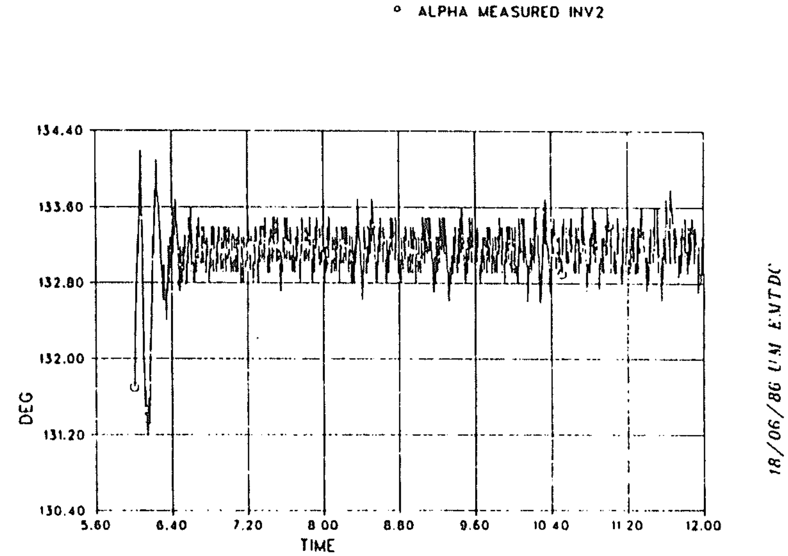
ALPHA RECTIFIER



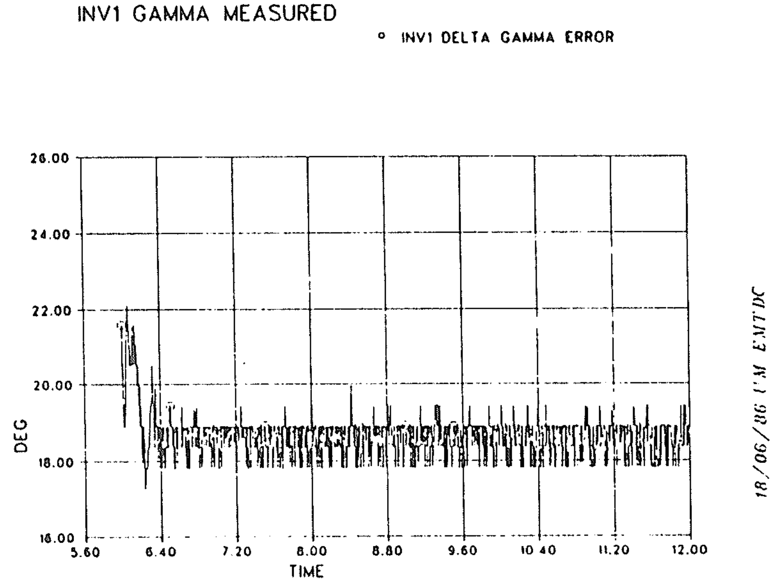
INV2 ALPHA ORDER OUT OF POLE CONTROLLER.



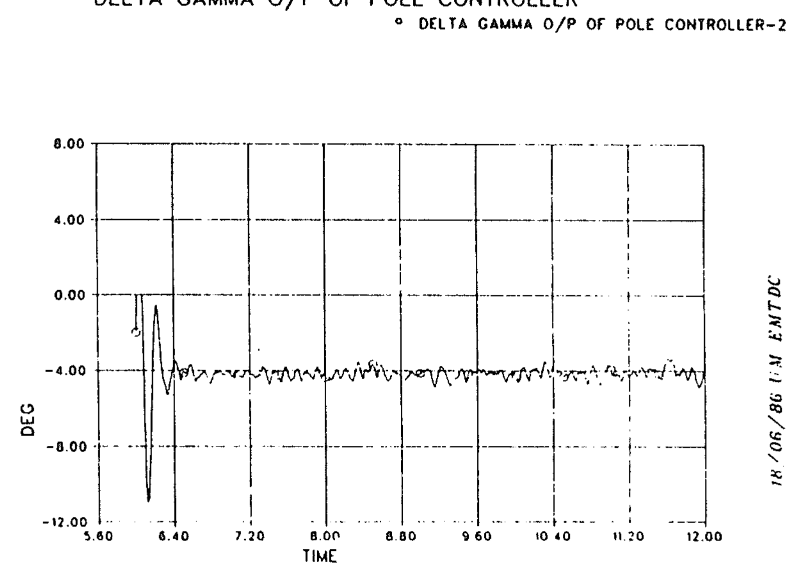
ALPHA MEASURED OF INV2

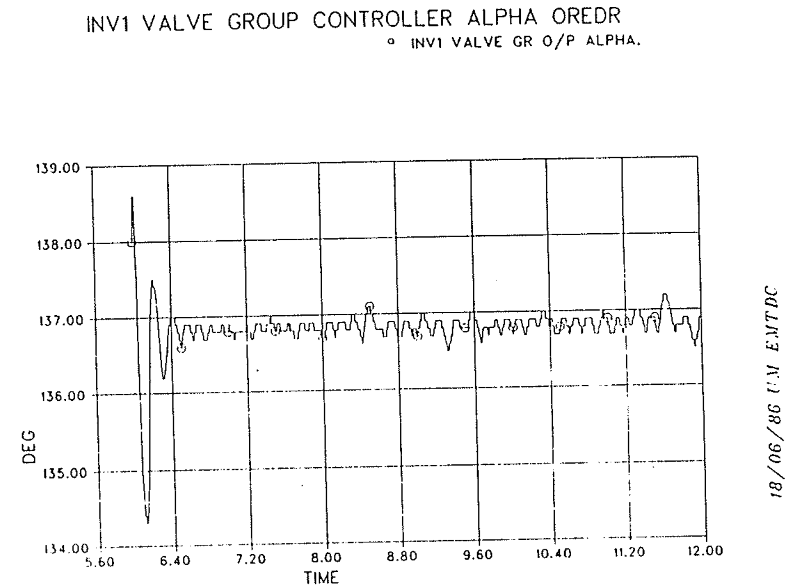


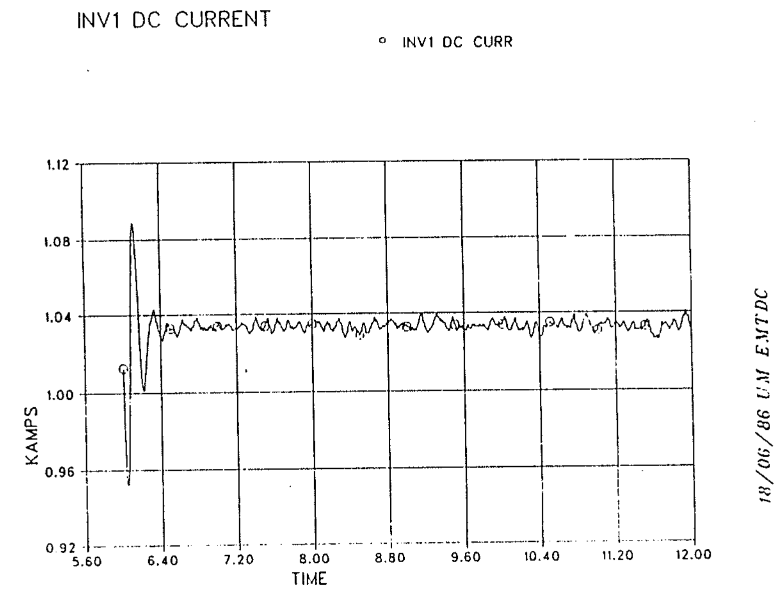
INV1 GAMMA MEASURED

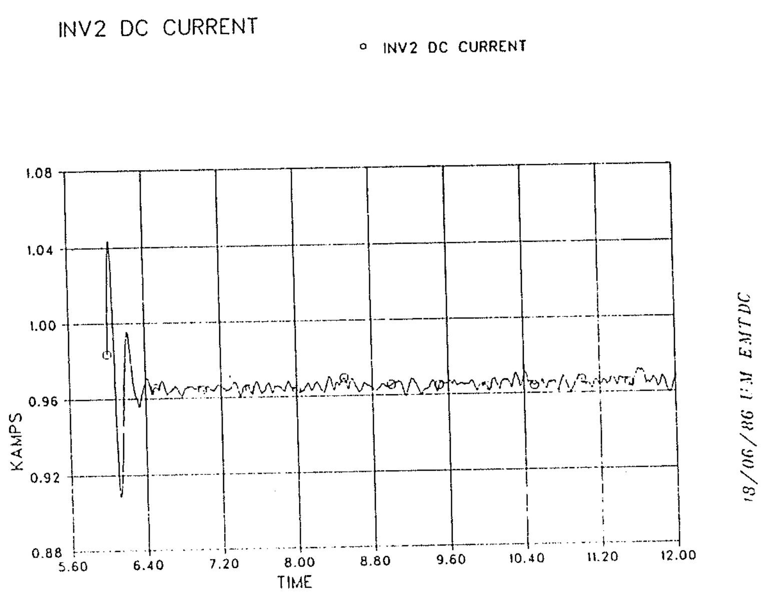


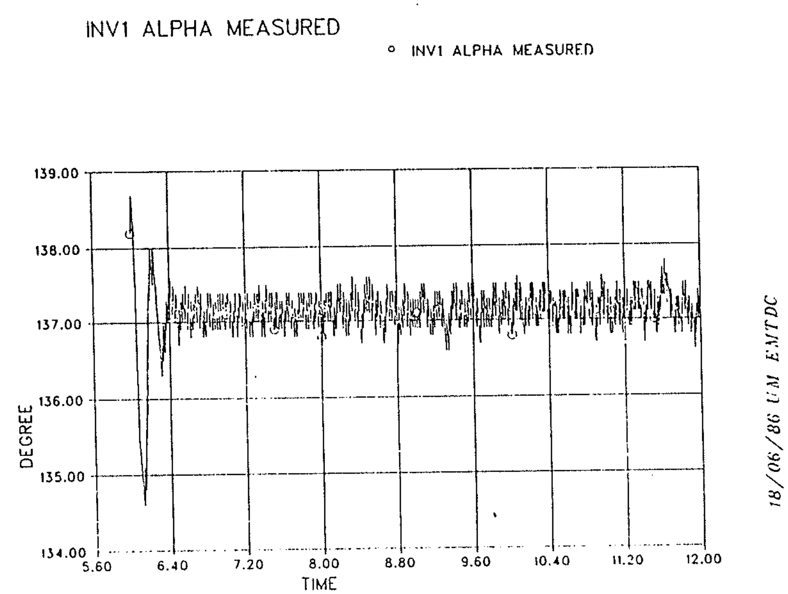
DELTA GAMMA O/P OF POLE CONTROLLER




INV1 VALVE GROUP CONTROLLER ALPHA OREDR
INV1 VALVE GR O/P ALPHA.
DEG
TIME
18/06/86 UM EMTDC

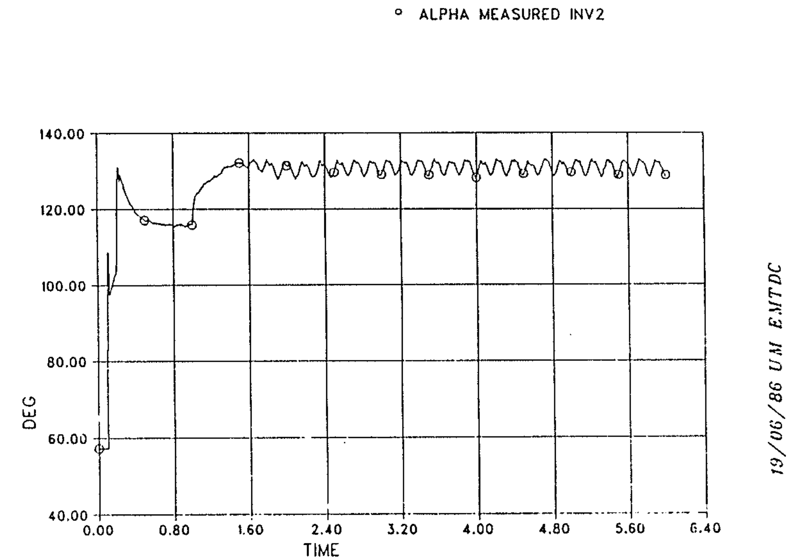

INV1 DC CURRENT
INV1 DC CURR
KAMPS
TIME
18/06/86 UM EMTDC


INV2 DC CURRENT
INV2 DC CURRENT
KAMPS
TIME
18/06/86 UM EMTDC

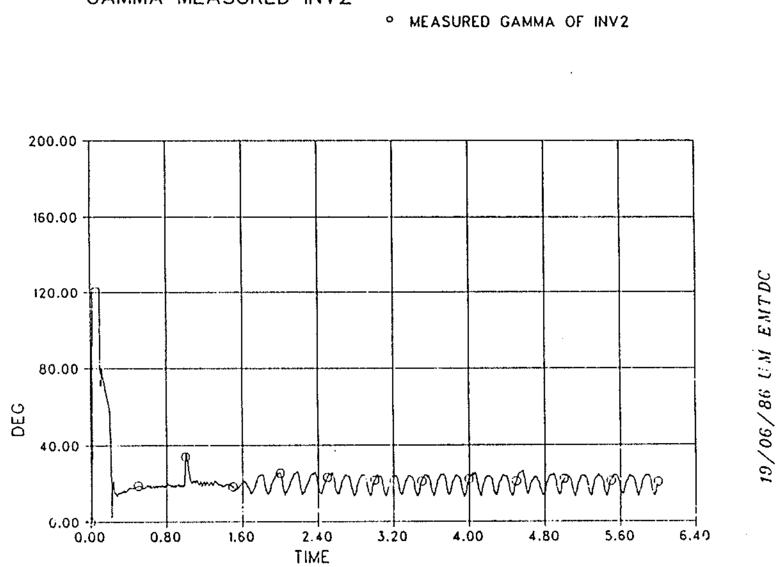

INV1 ALPHA MEASURED
INV1 ALPHA MEASURED
DEGREE
TIME
18/06/86 UM EMTDC

```
File DATA2 printed on Thu Jun 19 03:53:46 1986
--------------------------------------------------------------------------------------------------
    SIMPLE DC-AC SYSTEM /
0.00005 6.00 .0050 /THIS IS FROM FIXIT DIR
 / NO OF SUB SYSTEMS
 / NO OF NODE IN SS1
0 / INITIAL VOLTAGE
1 4 0.1 /SMALL RES
2 5 0.1 /SMALL RES
3 6 0.1 /SMALL RES
999 /
4 0.1 /SOURCE RESIST
5  0.1/
6  0.1 /
999 /
999 /
6 / SUB SYSTEM 2 IS HERE
0 /
1 3  0.0 1.72 /  LINE INDUCTANCE OF 2 H ASSUMED
3 5  0.0 0.55 / SMOOTHING REACTOR OF 1H FOR POLE1 INV1
3 6  0.0 0.37 / SMOOTHING REACTOR OF .75 FOR POLE1 INV2
3  0  0.0 0.0 .5 /.5 UF LINE TO GND.
5 2 0.0 0.55/
6 4 0.0 .37/
-5 0 4.42 0.195 1.0 /2X6th filter bpl
-5 0 5.50 0.122 0.4 /2X12th filter bpl
999 /
1 0.1 /SOURCE RES OF RECTIFIER
2 .1 /VALVE GROUP IS HERE FOR INV1 POLE1
4 .1 / VALVE GROUP IS HERE FOR INV2 POLE1
999 /
999 /
999 /
-10. 10./ PRINT PLOT LIMITS
20 / NO OF CHANNELS
186.6 0.020 2.0 600.0 0.02  1.0400
1.00  323.0 262.0 127.0 127.0 0.2 0.2 1.00 1.00 0.1 0.1
0.1 0.1 0.15 6.0 0.50 0.0150  0.020 0.020  2.00 0.5
3.14 1.0 1.0 0.00  0.15 2.80/ VAR(28) -POL1C7 INTEGRAL VAR(33)-VG1C36 ALPHA CON GAIN -DDA
999 /
)
```

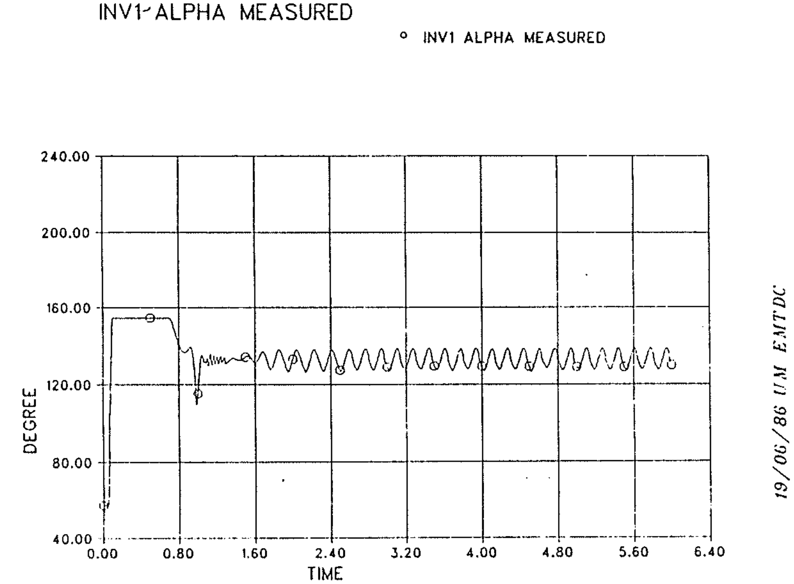
ALPHA MEASURED OF INV2

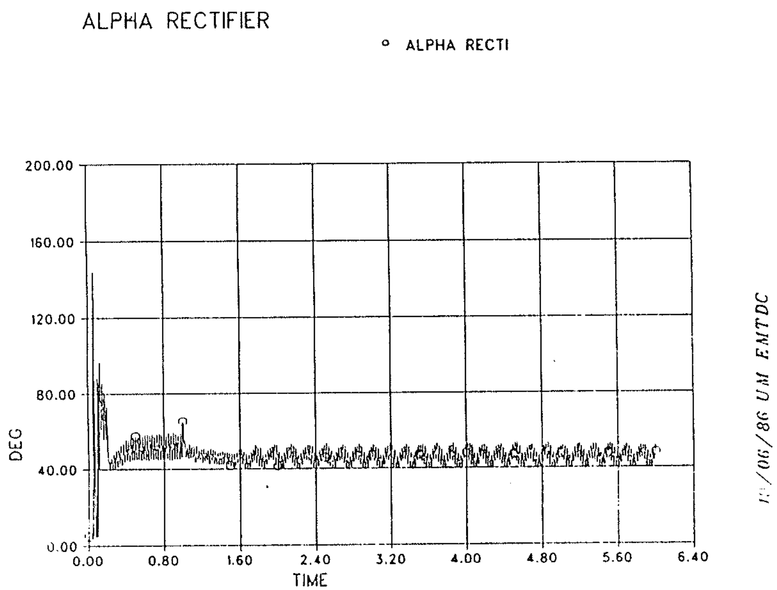


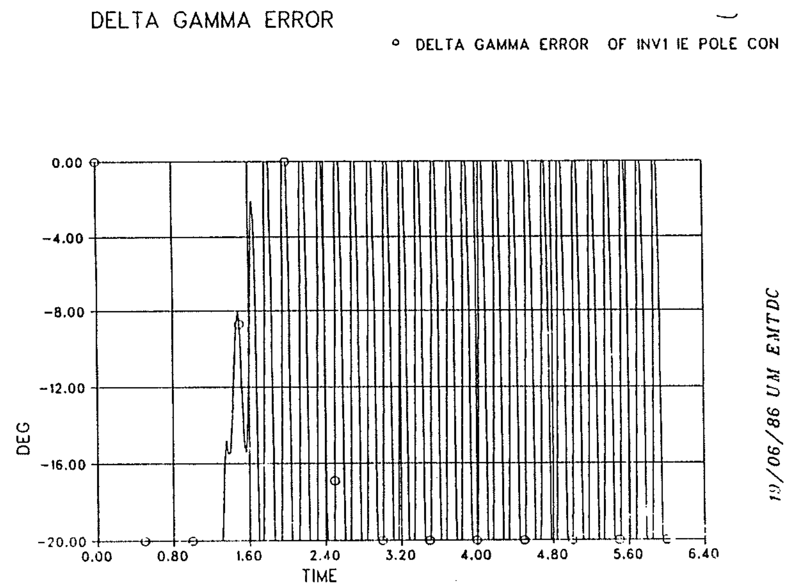
GAMMA MEASURED INV2

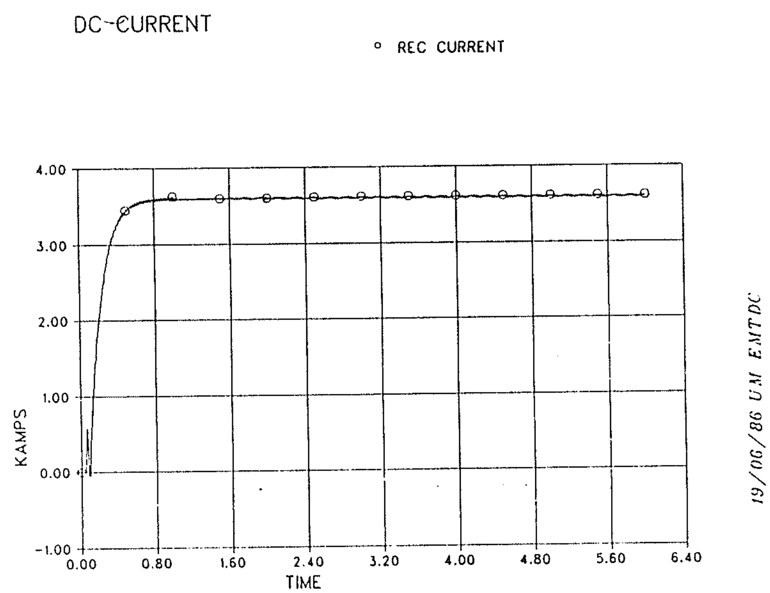


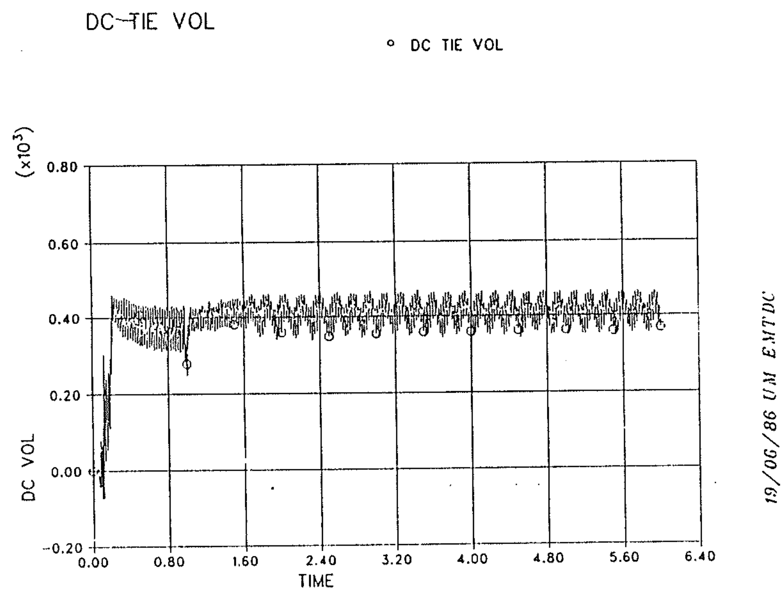
INV1-ALPHA MEASURED



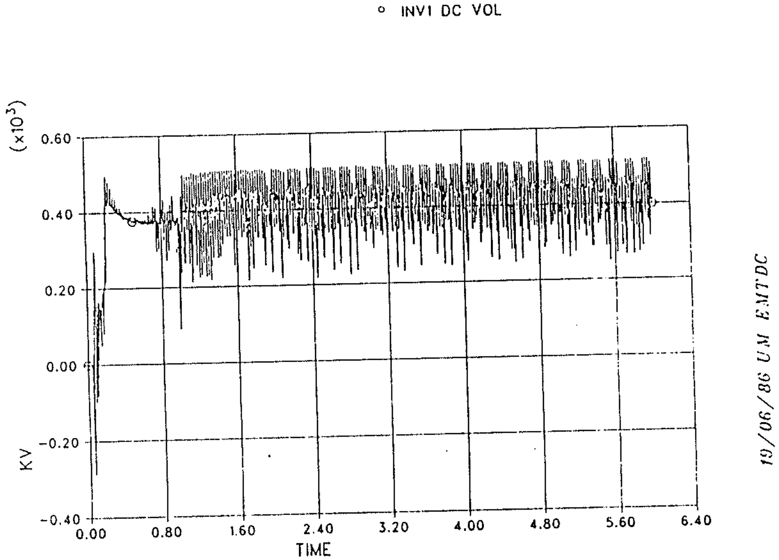

ALPHA RECTIFIER
ALPHA RECTI
200.00
160.00
120.00
80.00
40.00
0.00
DEG
0.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
TIME
UM EMTDC


DELTA GAMMA ERROR
DELTA GAMMA ERROR OF INV1 IE POLE CON O
0.00
-4.00
-8.00
-12.00
-16.00
-20.00
DEG
0.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
TIME
19/06/86 UM EMTDC

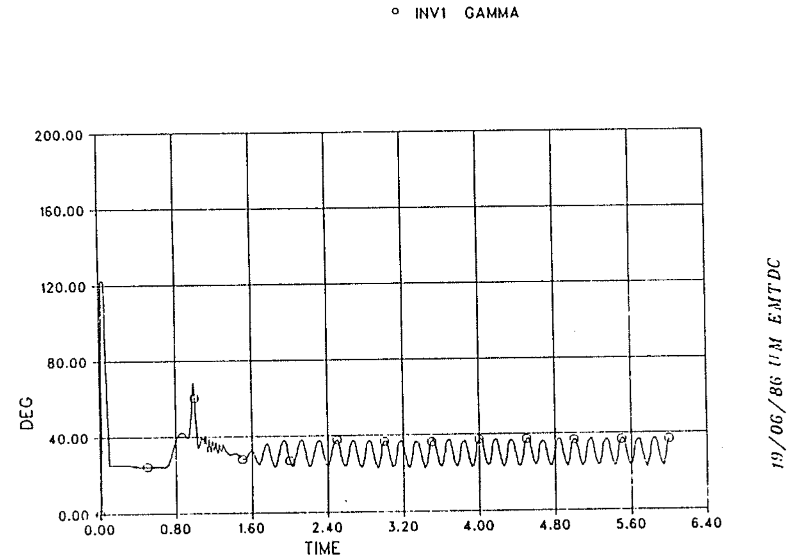

DC-CURRENT
REC CURRENT
4.00
3.00
2.00
1.00
0.00
-1.00
KAMPS
0.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
TIME
19/06/86 UM EMTDC


DC-TIE VOL
DC TIE VOL
(x10³)
0.80
0.60
0.40
0.20
0.00
-0.20
DC VOL
0.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
TIME
19/06/86 UM EMTDC

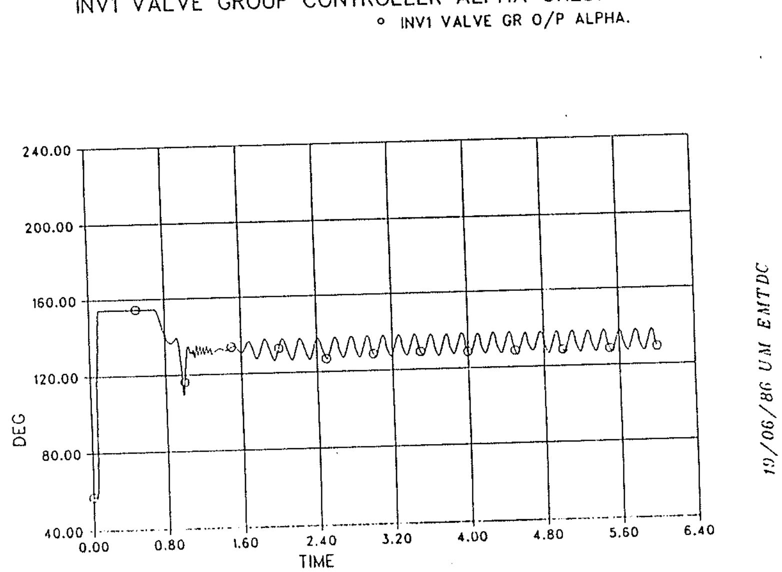
INV1-DC VOL



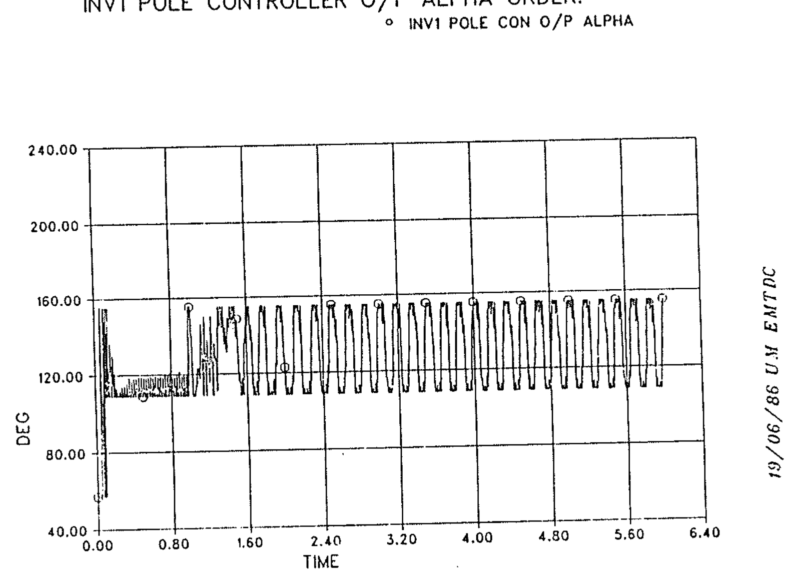
INV1-GAMMA MEASURED



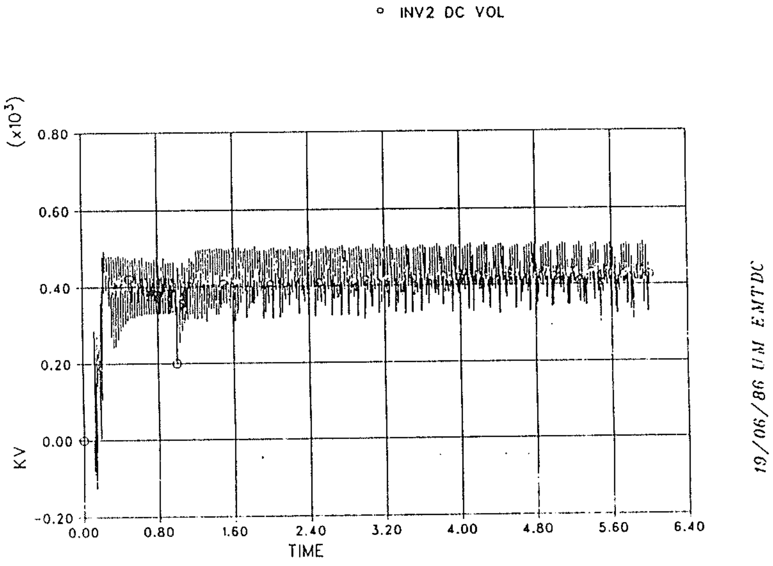
INV1 VALVE GROUP CONTROLLER ALPHA OREDR



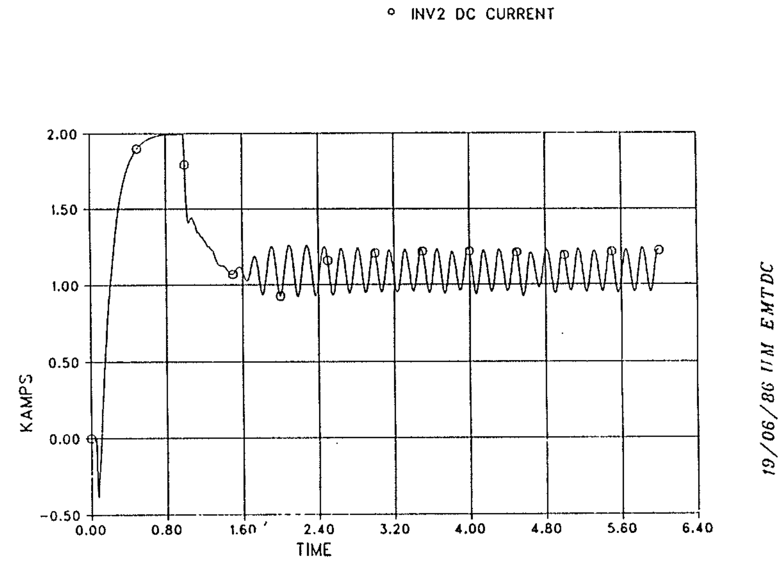
INV1 POLE CONTROLLER O/P ALPHA ORDER.



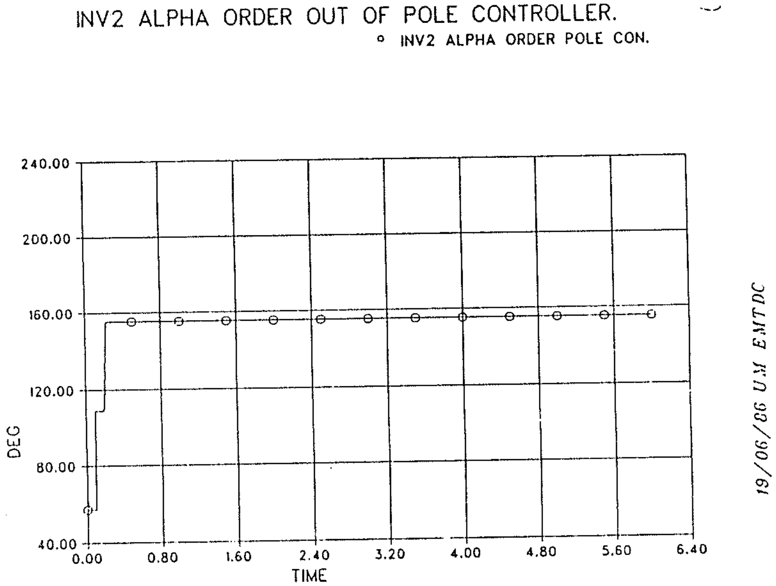
INV2 DC VOLTAGE



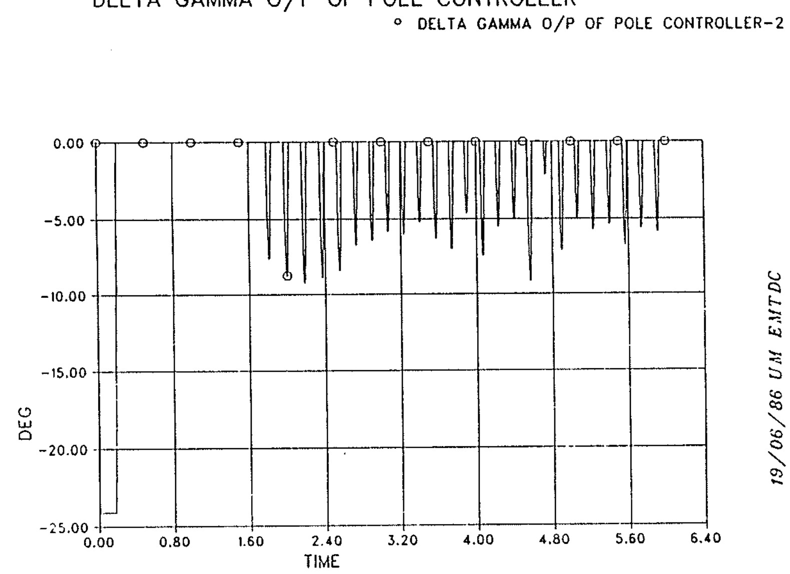
INV2 DC CURRENT



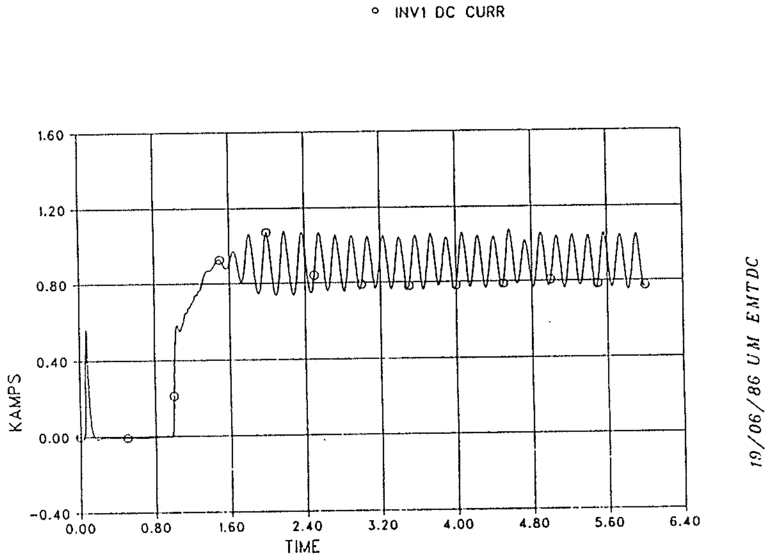
INV2 ALPHA ORDER OUT OF POLE CONTROLLER.



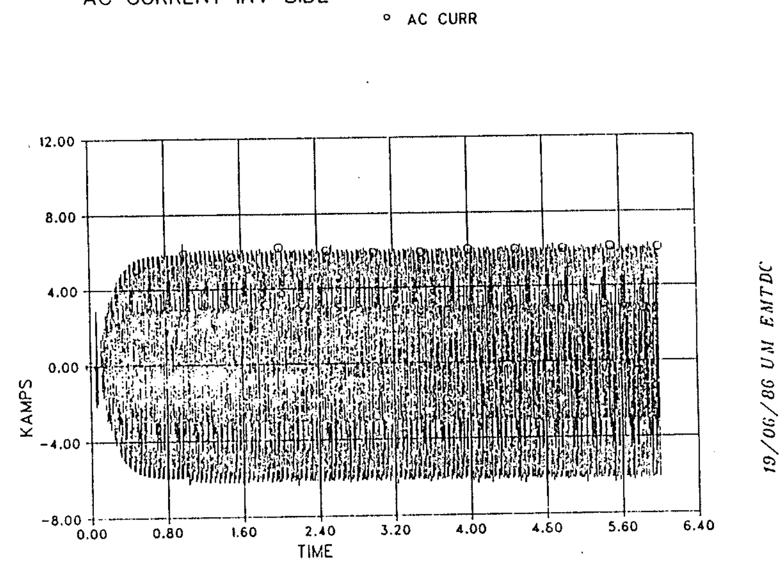
DELTA GAMMA O/P OF POLE CONTROLLER



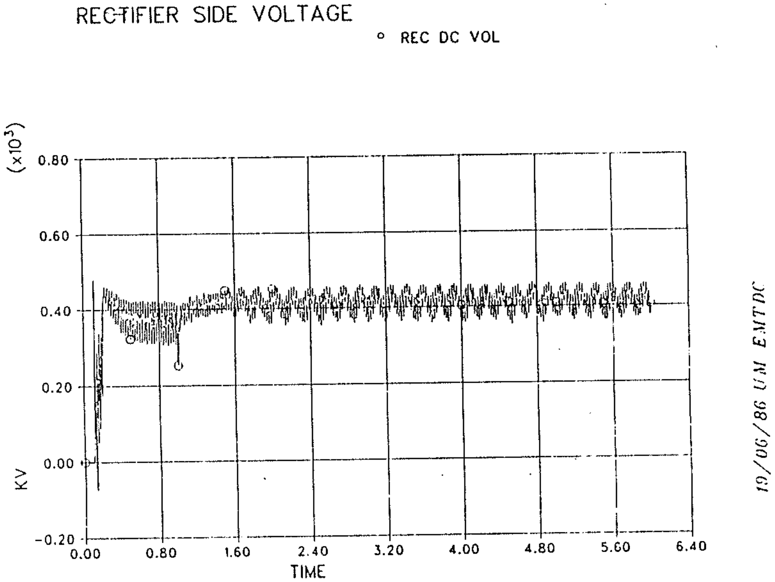
INV1 DC CURRENT



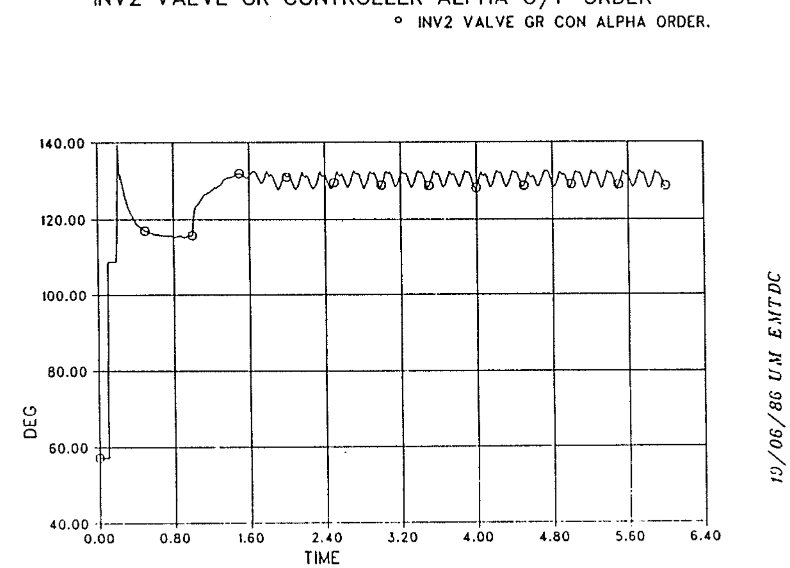
AC-CURRENT INV SIDE



RECTIFIER SIDE VOLTAGE



INV2 VALVE GR CONTROLLER ALPHA O/P ORDER

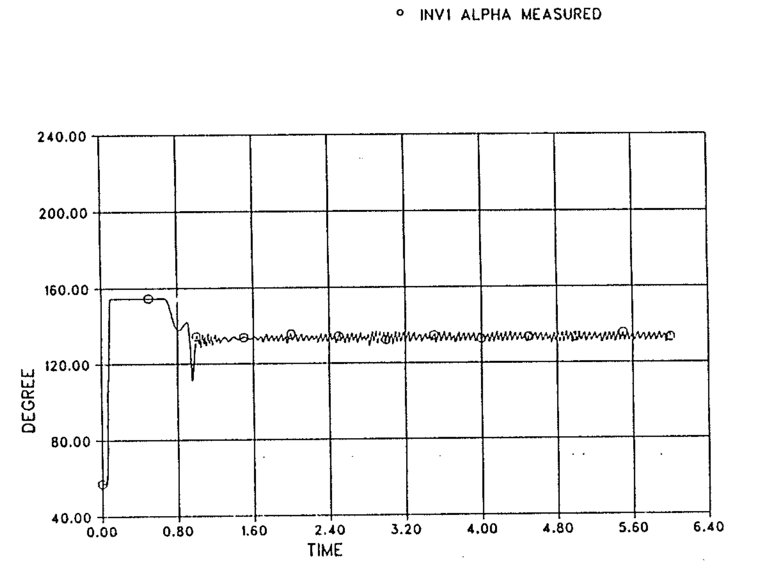


Appendix D

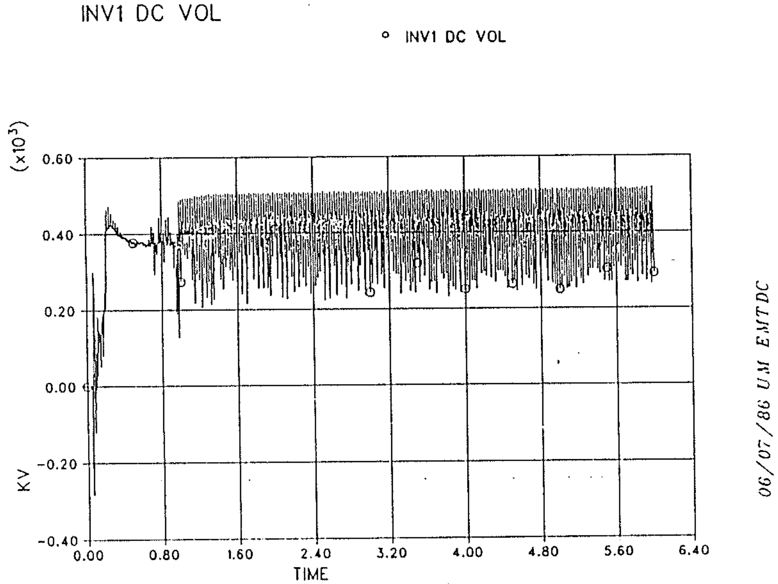
The following contains simulation results after suitable controller modification. Note the absence of limit cycle oscillation. Inverter 1 and inverter 2 converter transformer tap settings corresponds to the limit cycle oscillation case, when the controllers are in their original condition.

```
    SIMPLE DC-AC SYSTEM /
0.00005 6.00 .0050 /THIS IS FROM FIXIT DIR
` / NO OF SUB SYSTEMS
. / NO OF NODE IN SS1
0 / INITIAL VOLTAGE
1 4 0.1 /SMALL RES
2 5 0.1 /SMALL RES
3 6 0.1 /SMALL RES
999 /
4 0.1 /SOURCE RESIST
5  0.1/
6  0.1 /
999 /
999 /
6 / SUB SYSTEM 2 IS HERE
0 /
! 3  0.0 1.72 /  LINE INDUCTANCE OF 2 H ASSUMED
3 5  0.0 0.50 / SMOOTHING REACTOR OF .5H FOR POLE1 INV1 IS REMOVED.
3 6  0.0 0.37 / SMOOTHING REACTOR OF .75 FOR POLE1 INV2
3  0  0.0 0.0 .5 /.5 UF LINE TO GND.
5 2 0.0 0.55/
6 4 0.0 .37/
-5 0 4.42 0.195 1.0 /2X6th filter bpl
-5 0 5.50 0.122 0.4 /2X12th filter bpl
999 /
1 0.1 /SOURCE RES OF RECTIFIER
2 .1 /VALVE GROUP IS HERE FOR INV1 POLE1
4 .1 / VALVE GROUP IS HERE FOR INV2 POLE1
999 /
999 /
999 /
-10. 10./ PRINT PLOT LIMITS
20 / NO OF CHANNELS
186.6 0.020 2.0 600.0 0.02  1.0400
1.00  323.0 262.0 127.0 127.0 0.2 0.2 1.00 1.00 0.1 0.1
0.1 0.1 0.15 6.0 0.50 0.0150  0.020 0.020  2.00 0.5
3.14 1.0 1.0 0.00  0.20 2.80  0.8  25.0  1.000 1.00/ VAR(28) -POL1C7 INTEGRAL VAR(33)-VG1C36 ALPHA CON GAIN -DDA
999 / POL1C7 DGE TIME CONSTANT DECREASED BY A FACTOR OF 25.0 AND GAIN BY 0.8
ACCORDING TO BOB HAMLIN'S REQUEST LINE SIDE OF INV1 SMOOTHING INDUCTOR
IS PUT TO ZERO.
```

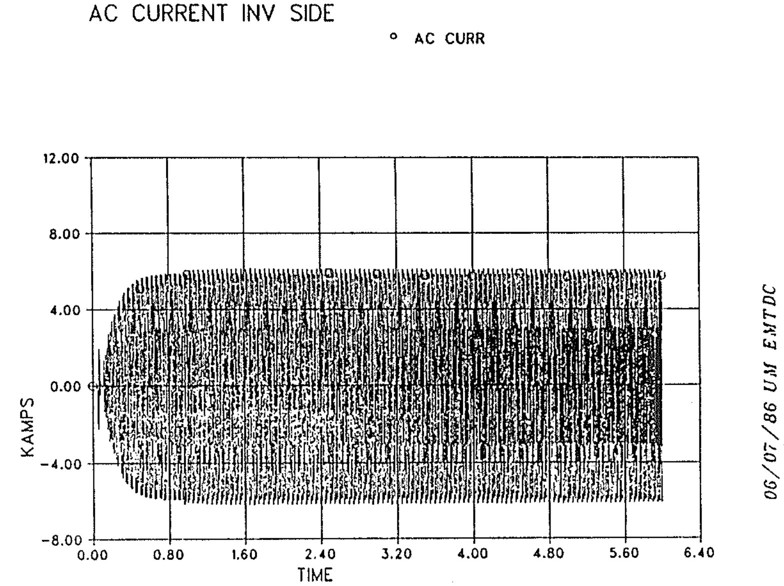
INV1 ALPHA MEASURED

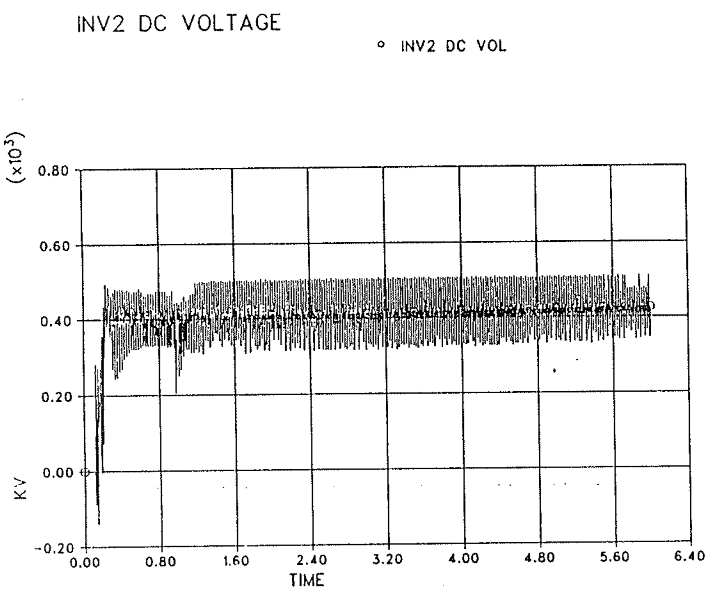


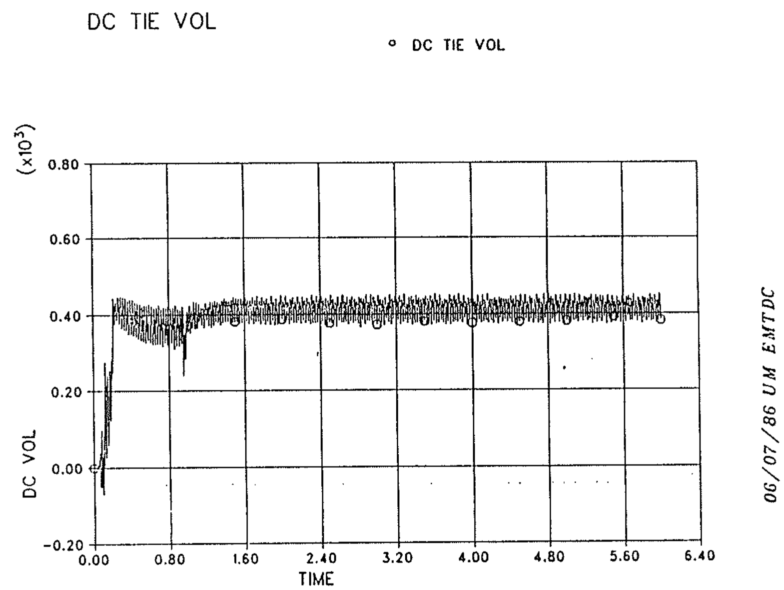
INV1 DC VOL

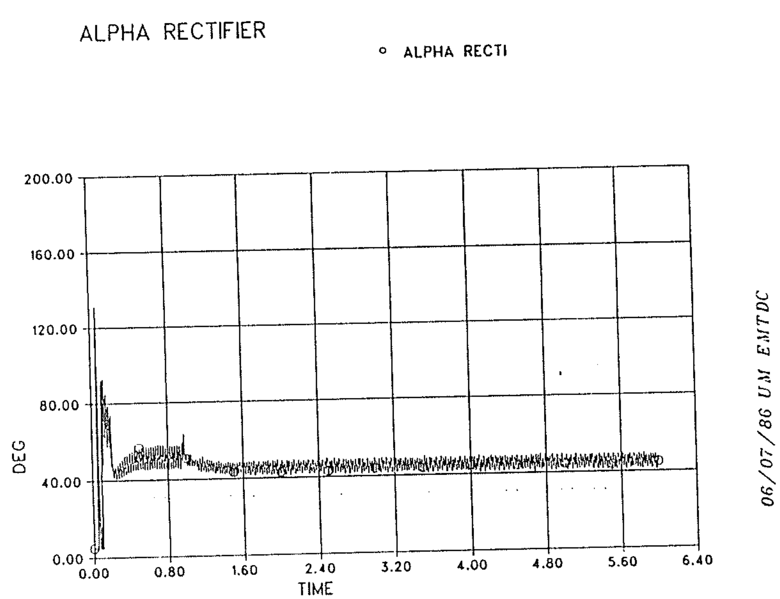


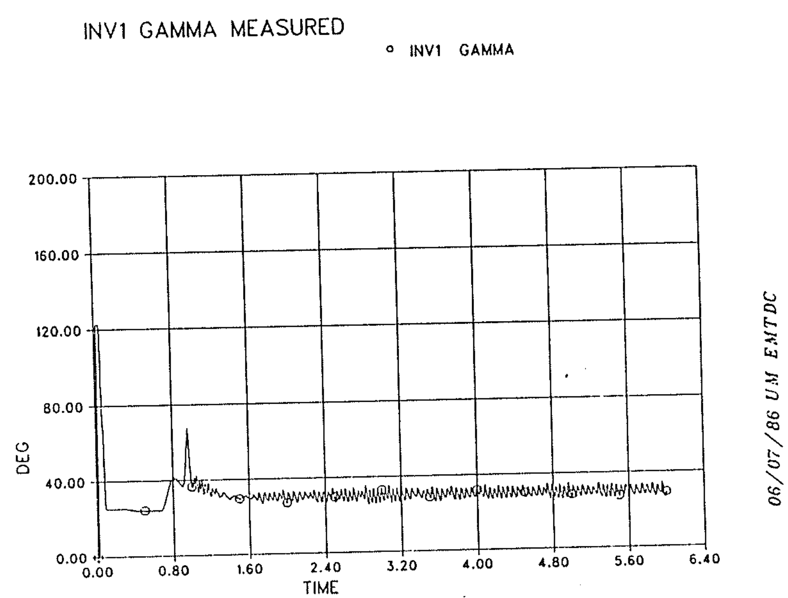
AC CURRENT INV SIDE



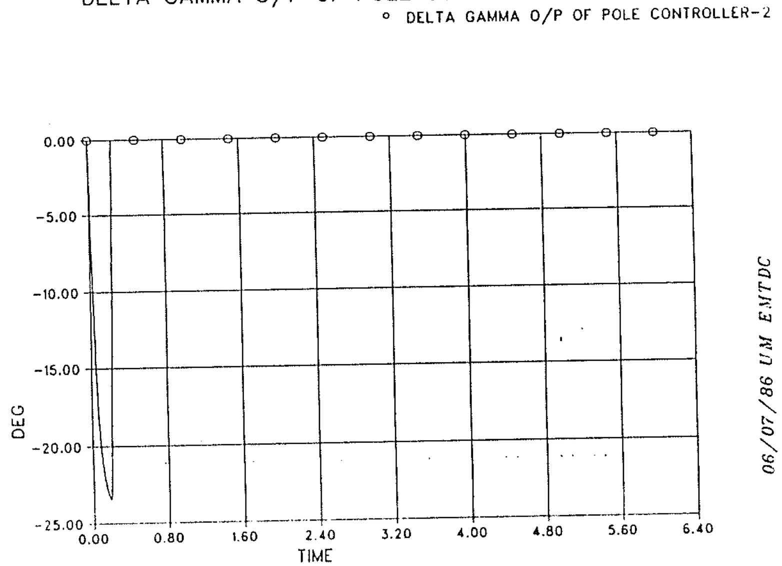

INV2 DC VOLTAGE
o INV2 DC VOL
(x10^3)
KV
0.80
0.60
0.40
0.20
0.00
-0.20
0.00 0.80 1.60 2.40 3.20 4.00 4.80 5.60 6.40
TIME
06/07/86 UM EMTDC


DC TIE VOL
o DC TIE VOL
(x10^3)
DC VOL
0.80
0.60
0.40
0.20
0.00
-0.20
0.00 0.80 1.60 2.40 3.20 4.00 4.80 5.60 6.40
TIME
06/07/86 UM EMTDC

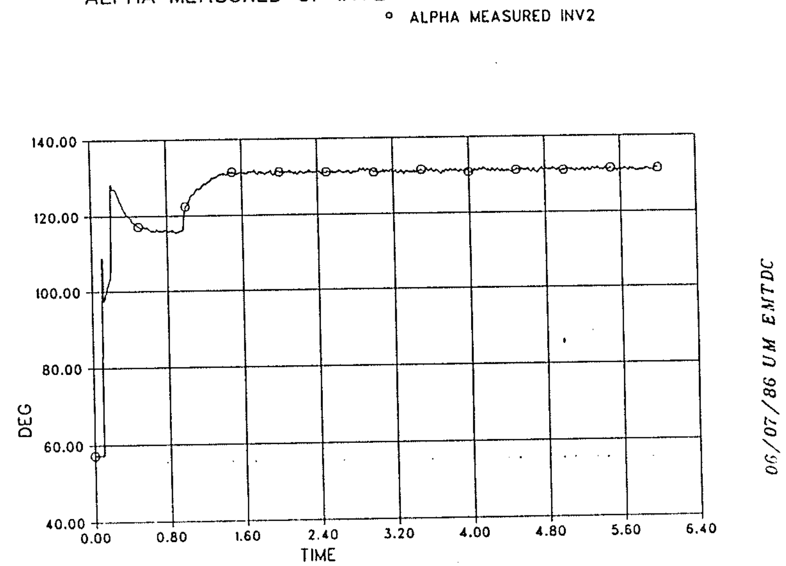

ALPHA RECTIFIER
o ALPHA RECTI
DEG
200.00
160.00
120.00
80.00
40.00
0.00
0.00 0.80 1.60 2.40 3.20 4.00 4.80 5.60 6.40
TIME
06/07/86 UM EMTDC


INV1 GAMMA MEASURED
o INV1 GAMMA
DEG
200.00
160.00
120.00
80.00
40.00
0.00
0.00 0.80 1.60 2.40 3.20 4.00 4.80 5.60 6.40
TIME
06/07/86 UM EMTDC

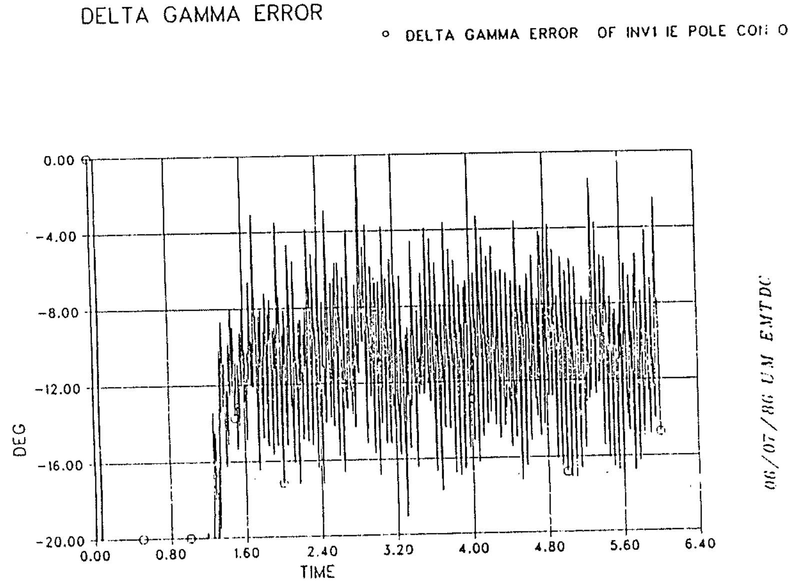
DELTA GAMMA O/P OF POLE CONTROLLER



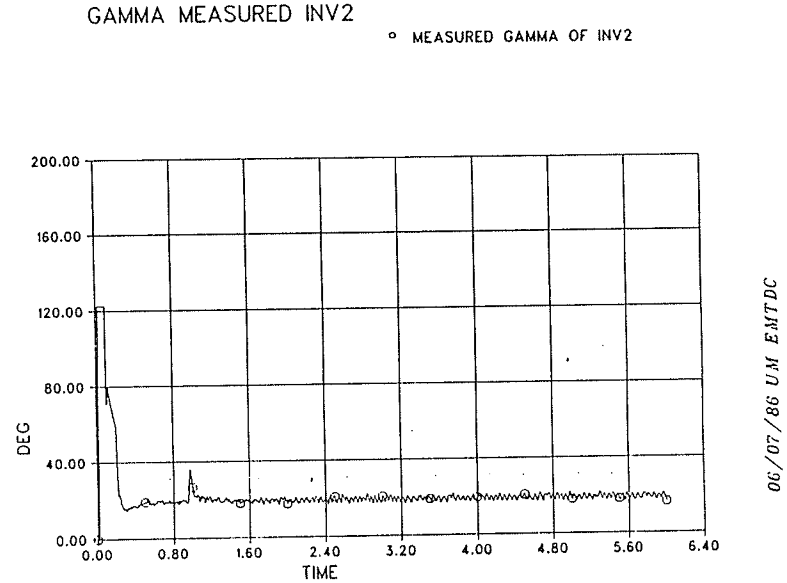
ALPHA MEASURED OF INV2



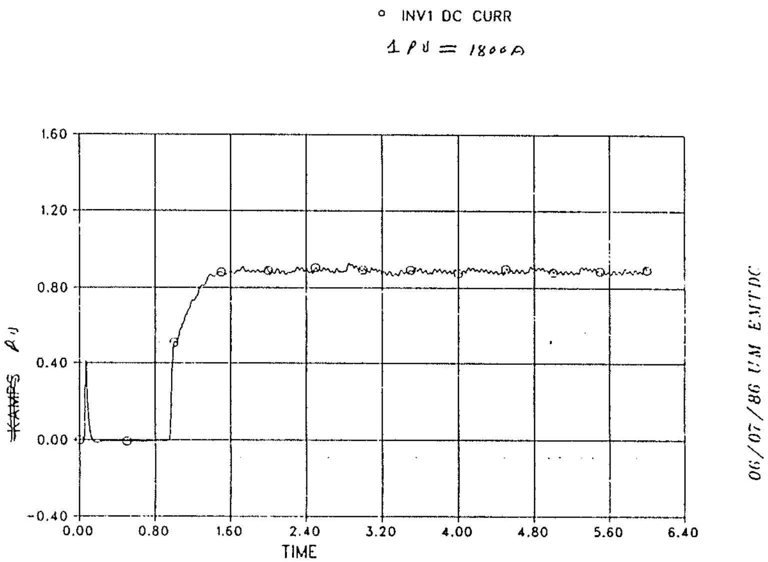
DELTA GAMMA ERROR



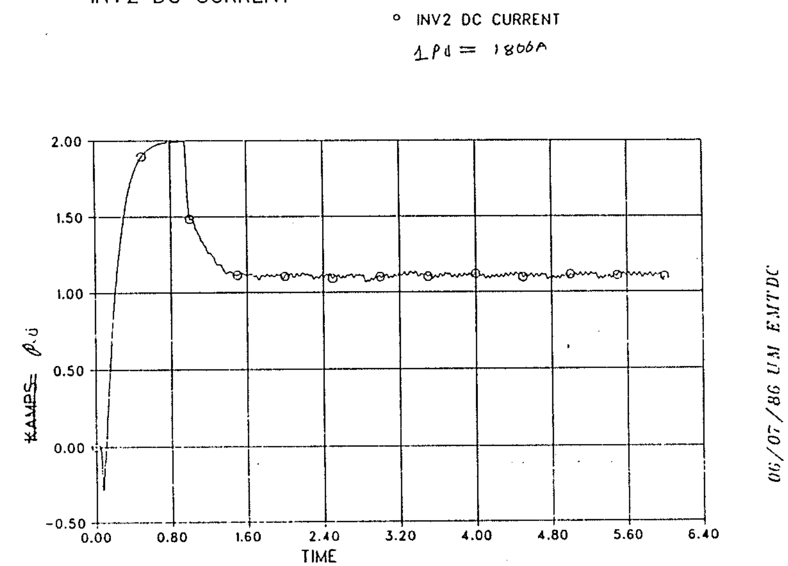
GAMMA MEASURED INV2



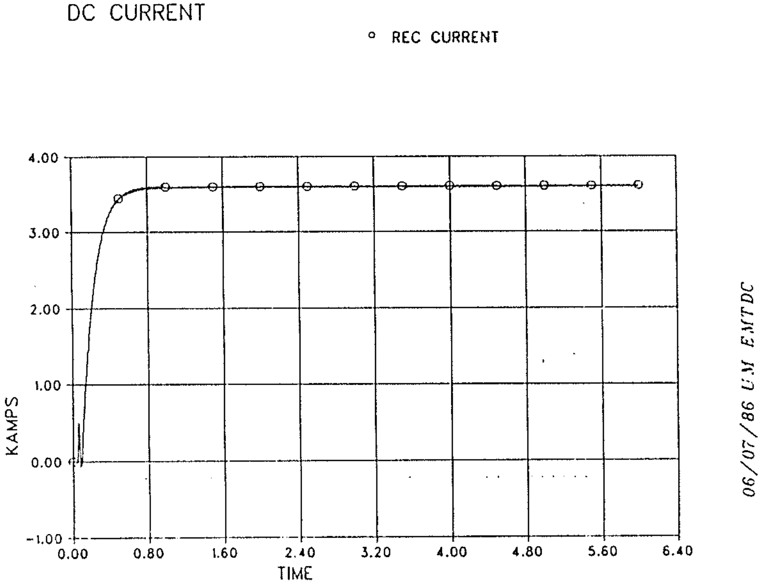
INV1 DC CURRENT



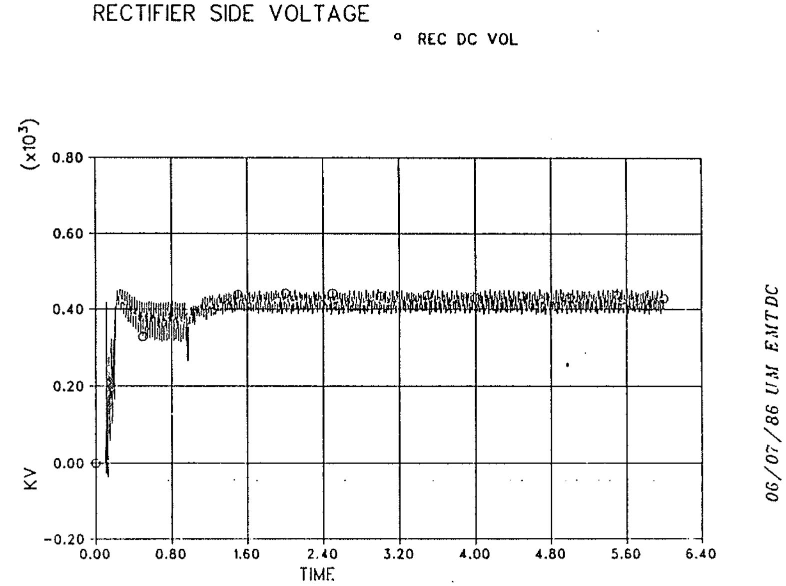
INV2 DC CURRENT



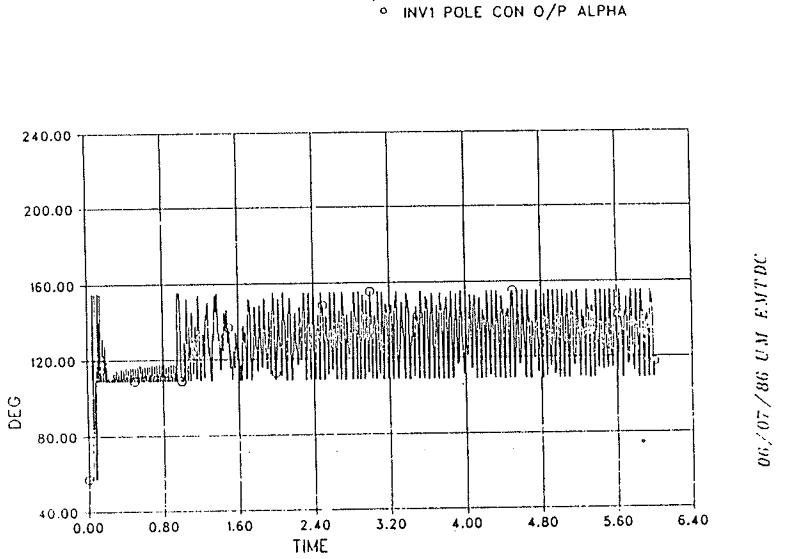
DC CURRENT



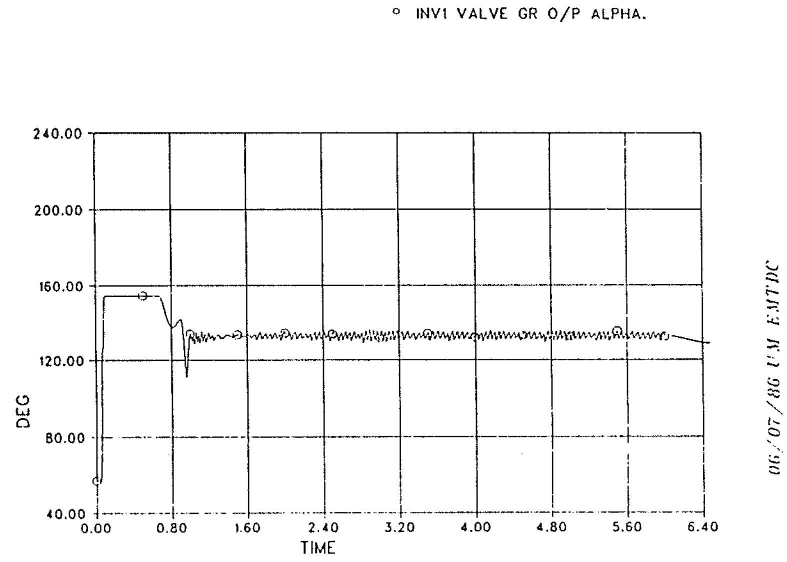
RECTIFIER SIDE VOLTAGE



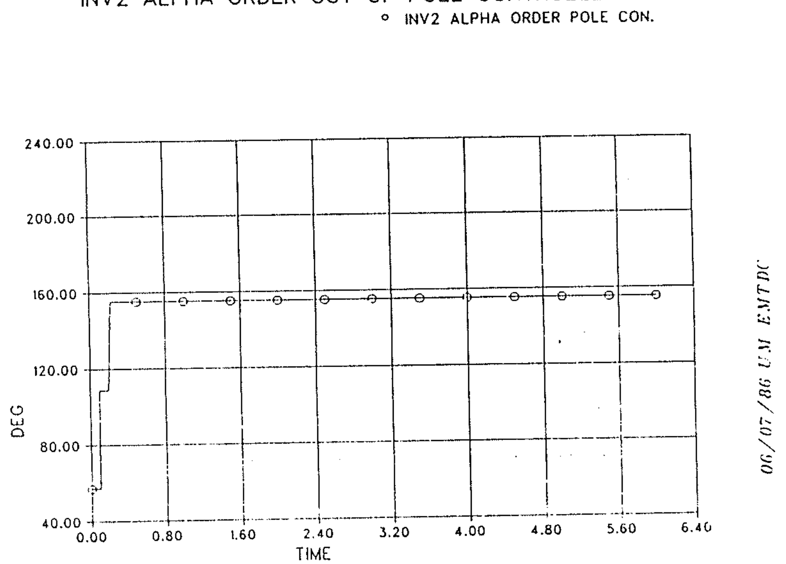
INV1 POLE CONTROLLER O/P ALPHA ORDER.



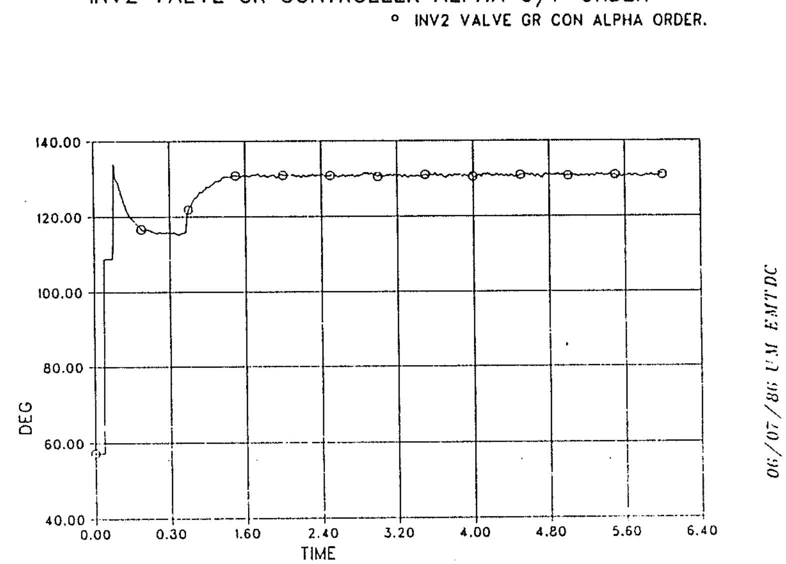
INV1 VALVE GROUP CONTROLLER ALPHA OREDR



INV2 ALPHA ORDER OUT OF POLE CONTROLLER.



INV2 VALVE GR CONTROLLER ALPHA O/P ORDER

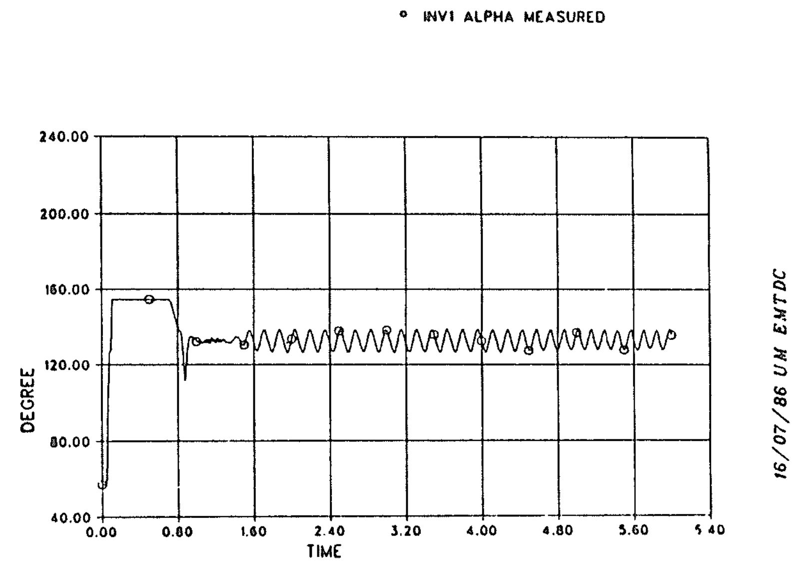


Appendix E

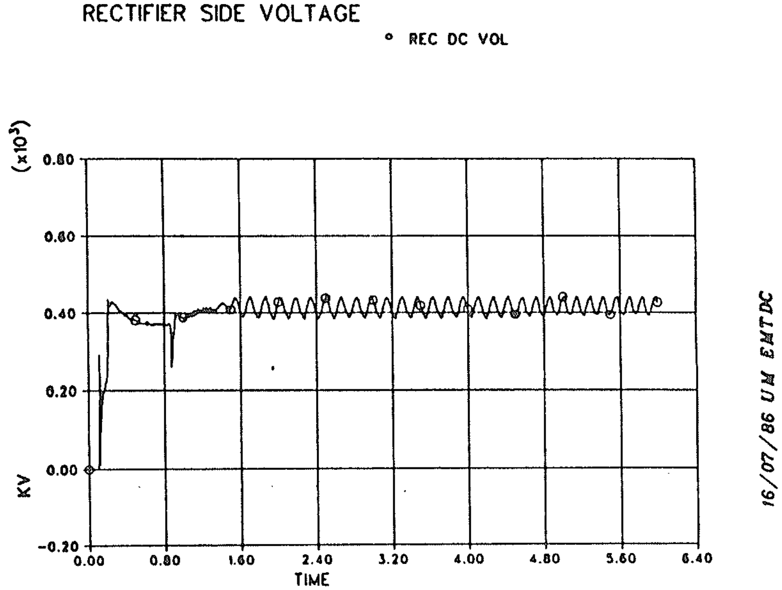
The following contains the simulation results, which confirms the field observation that when inverter 1 smoothing reactor is removed from service, a limit cycle oscillation of 7.5 hz is observed among the inverters.

```
7   SIMPLE DC-AC SYSTEM /
).00005 6.00 .0050 /THIS IS FROM FIXIT DIR
 ` / NO OF SUB SYSTEMS
3 / NO OF NODE IN SS1
0 / INITIAL VOLTAGE
1 4 0.1 /SMALL RES
2 5 0.1 /SMALL RES
3 6 0.1 /SMALL RES
999 /
4 0.1 /SOURCE RESIST
6  0.1/
6  0.1 /
999 /
999 /
6 / SUB SYSTEM 2 IS HERE
0 /
1 3  0.0 1.72 /  LINE INDUCTANCE OF 2 H ASSUMED
3 5  0.1 / SMOOTHING REACTOR OF .5H FOR POLE1 INV1 IS REMOVED.
3 6  0.0 0.37 / SMOOTHING REACTOR OF .75 FOR POLE1 INV2
-3  0  0.0 0.0 .5 /.5 UF LINE TO GND.
5 2 0.0 0.55/
6 4 0.0 .37/
-3 0 100.0 .02036 0.6 / BP2 HIGH PASS FILTER
-3 0 7.94 0.1222 0.4 / BP2 12TH HARMONIC FILTER
-5 0 4.42 0.195 1.0 /2X6th filter bp1
-5 0 5.50 0.122 0.4 /2X12th filter bp1
999 /
1 0.1 /SOURCE RES OF RECTIFIER
2 .1 /VALVE GROUP IS HERE FOR INV1 POLE1
4 .1 / VALVE GROUP IS HERE FOR INV2 POLE1
999 /
999 /
999 /
-10. 10./ PRINT PLOT LIMITS
20 / NO OF CHANNELS
186.6 0.020 2.0 600.0 0.02  1.0400
1.00  323.0 262.0 127.0 127.0 0.2 0.2 1.00 1.00 0.1 0.1
9.1 0.1 0.15 6.0 0.50 0.0150  0.020 0.020  2.00 0.5
3.14 1.0 1.0 0.00  0.20 2.00  1.0  1.00  1.000 1.00/ VAR(28) =POL1C7 INTEGRAL VAR(33)=VG1C36 ALPHA CON GAIN  DOA
.99 / POL1C7 DGE TIME CONSTANT DECREASED BY A FACTOR OF 25.0 AND GAIN BY 0.8
ACCORDING TO BOB HAMLIN'S REQUEST LINE SIDE OF INV1 SMOOTHING INDUCTOR
IS PUT TO ZERO.
```

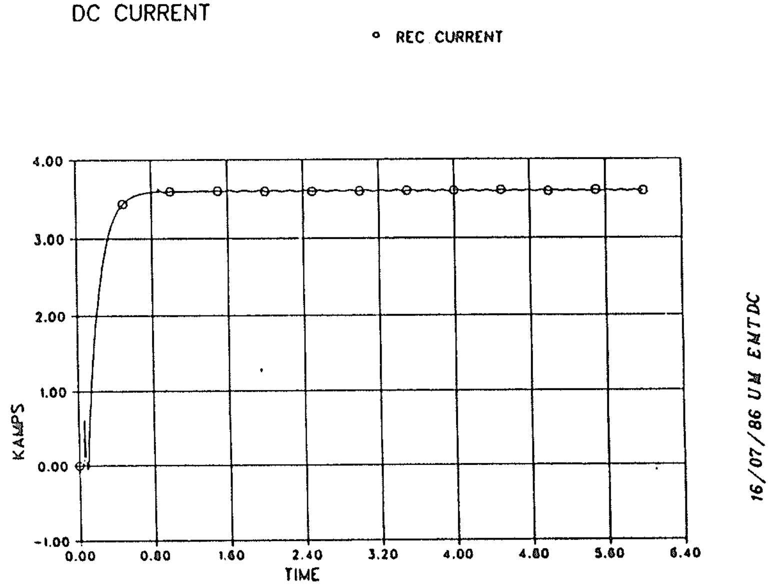
INV1 ALPHA MEASURED



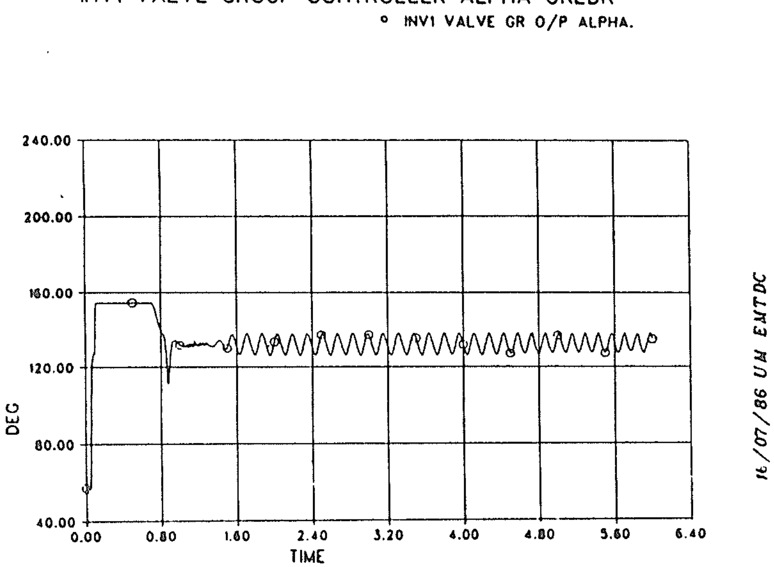
RECTIFIER SIDE VOLTAGE



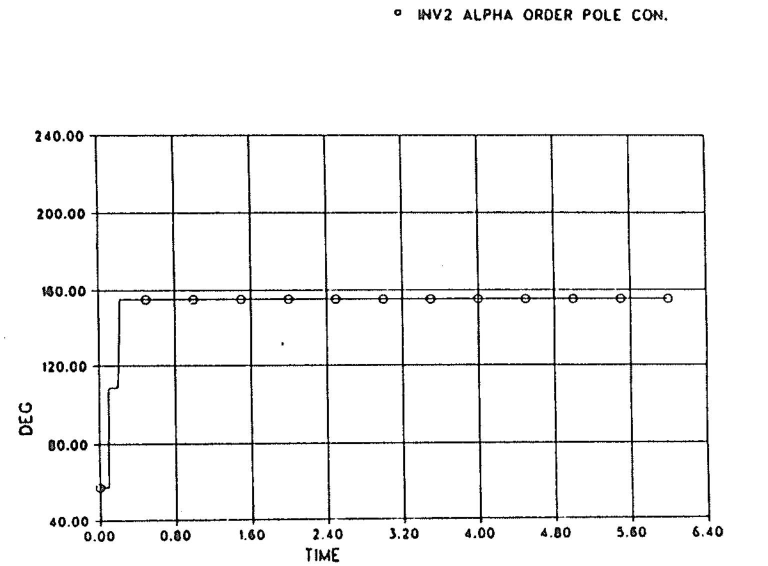
DC CURRENT



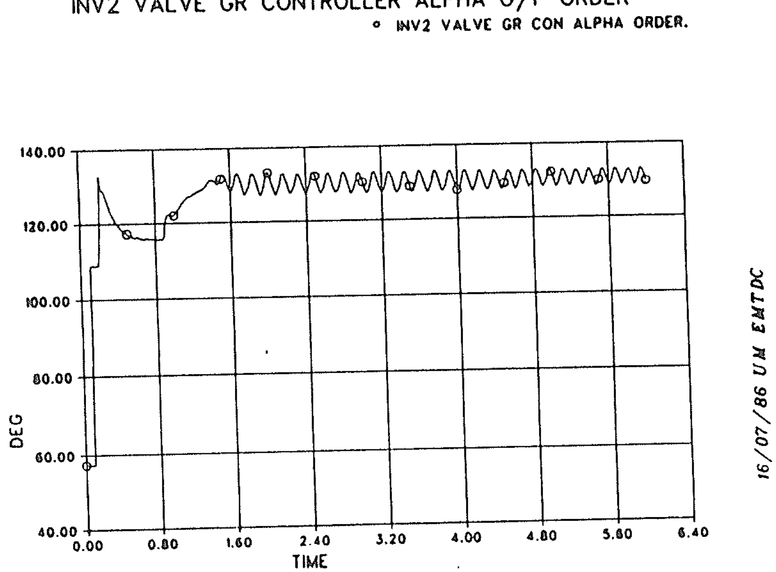
INV1 VALVE GROUP CONTROLLER ALPHA OREDR



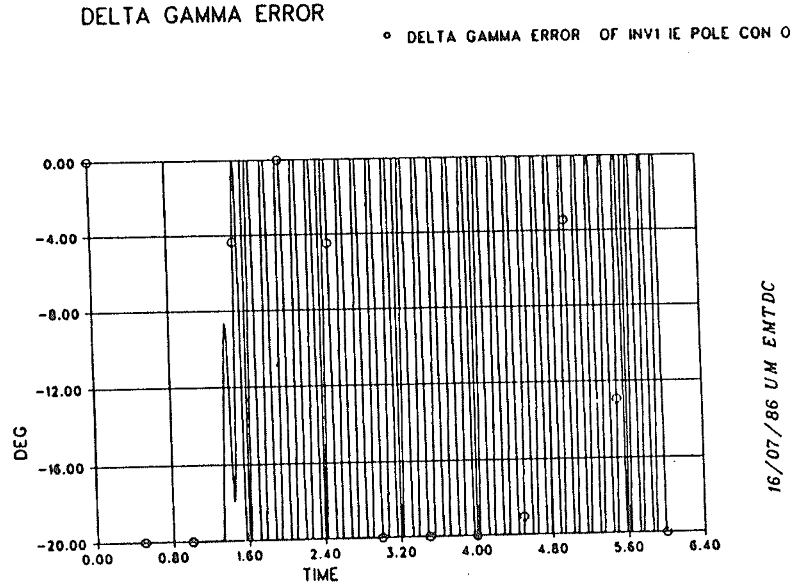
INV2 ALPHA ORDER OUT OF POLE CONTROLLER.

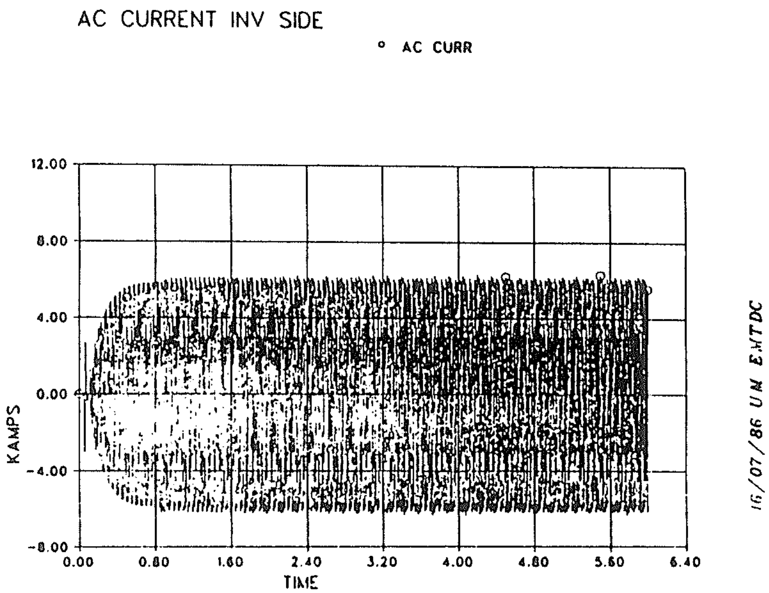


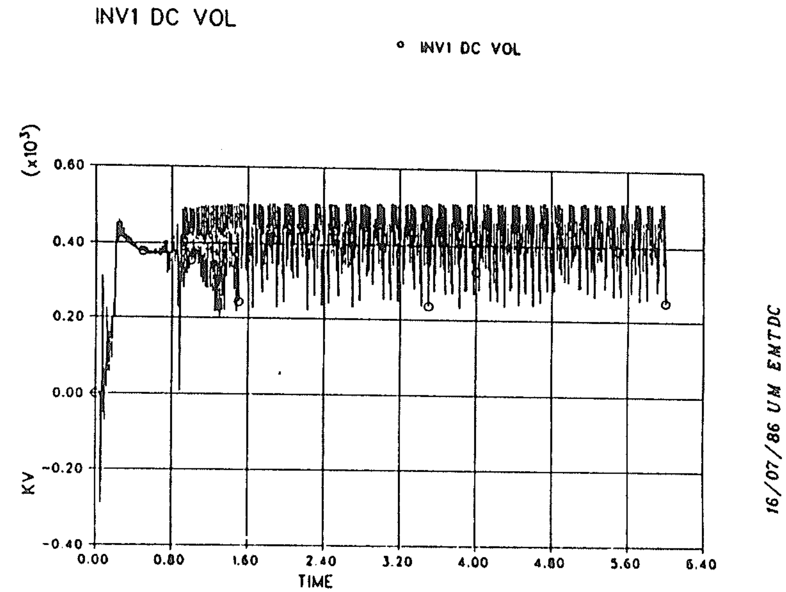
INV2 VALVE GR CONTROLLER ALPHA O/P ORDER

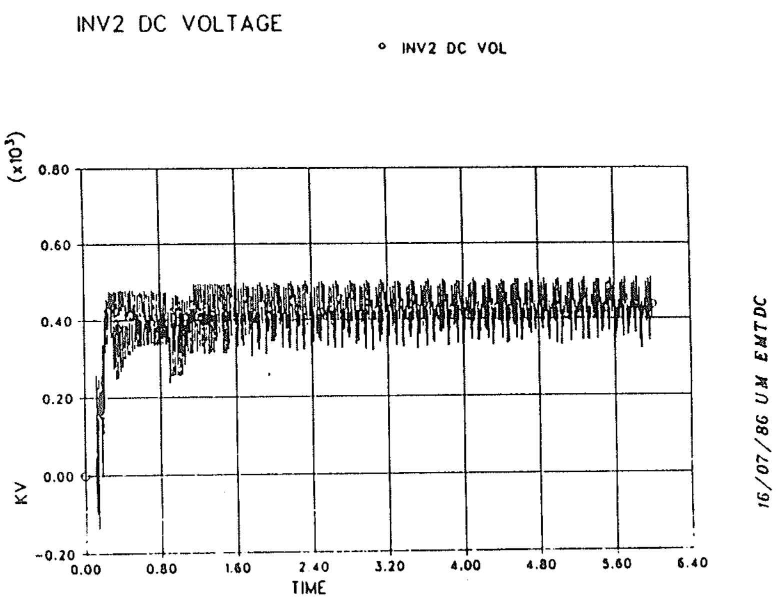


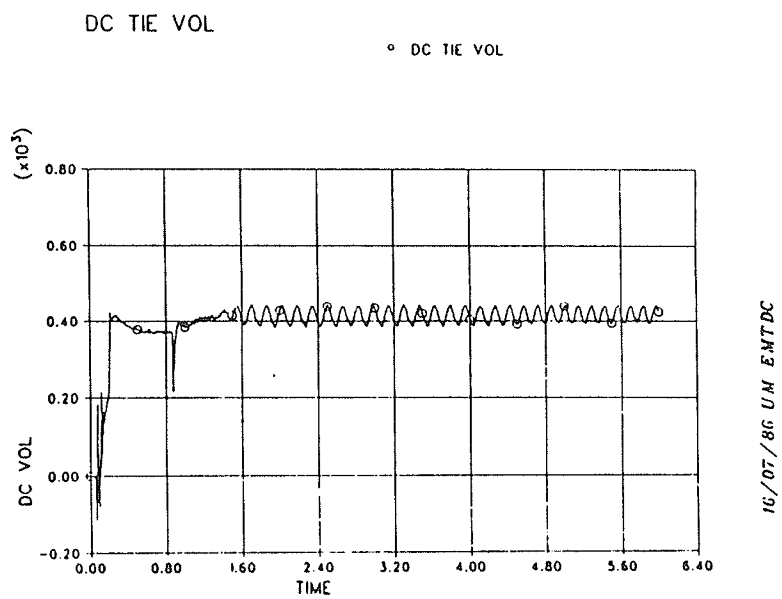
DELTA GAMMA ERROR

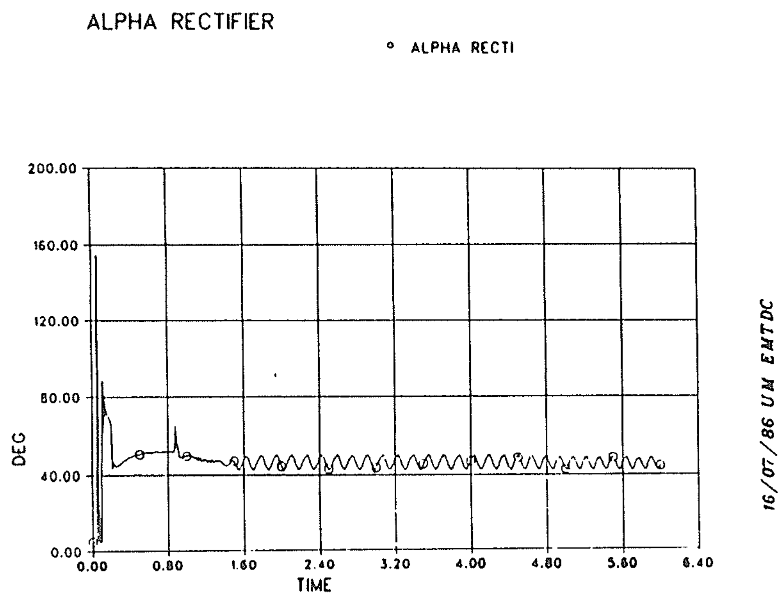


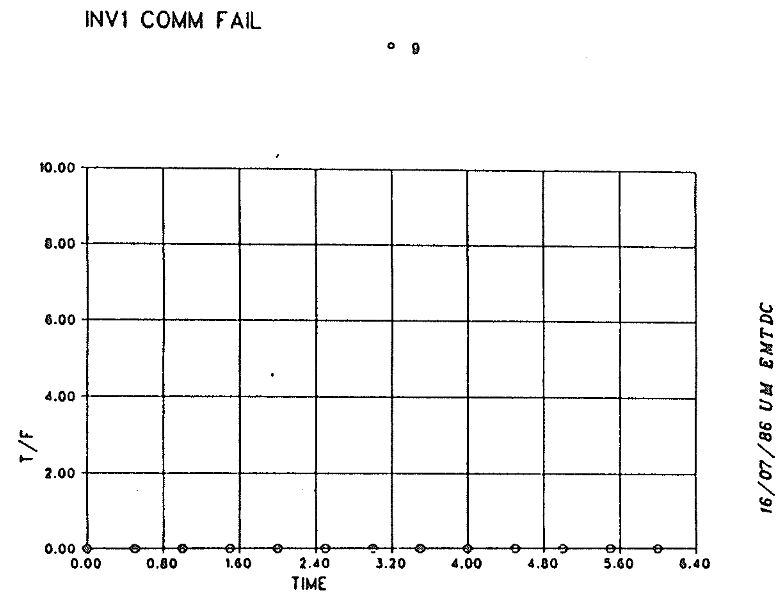

AC CURRENT INV SIDE
AC CURR
KAMPS
TIME
16/07/86 UM EMTDC

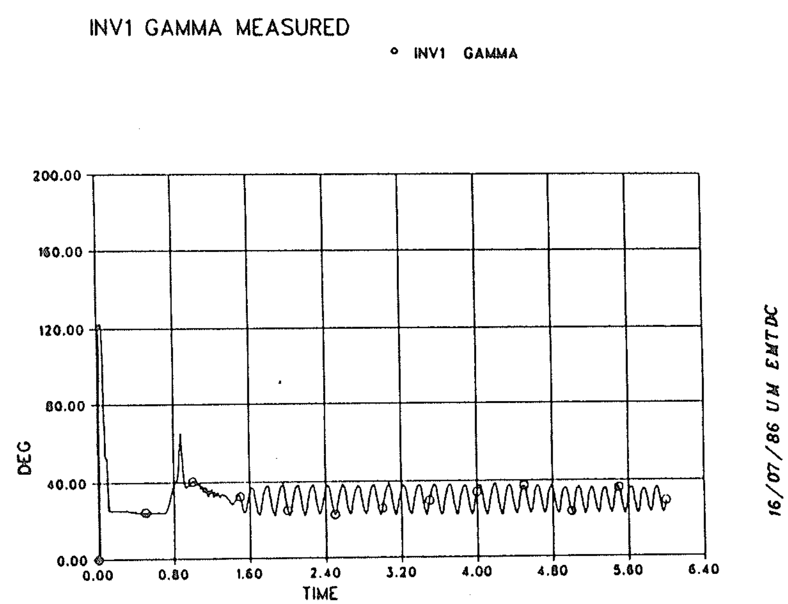

INV1 DC VOL
INV1 DC VOL
(x10³)
KV
TIME
16/07/86 UM EMTDC

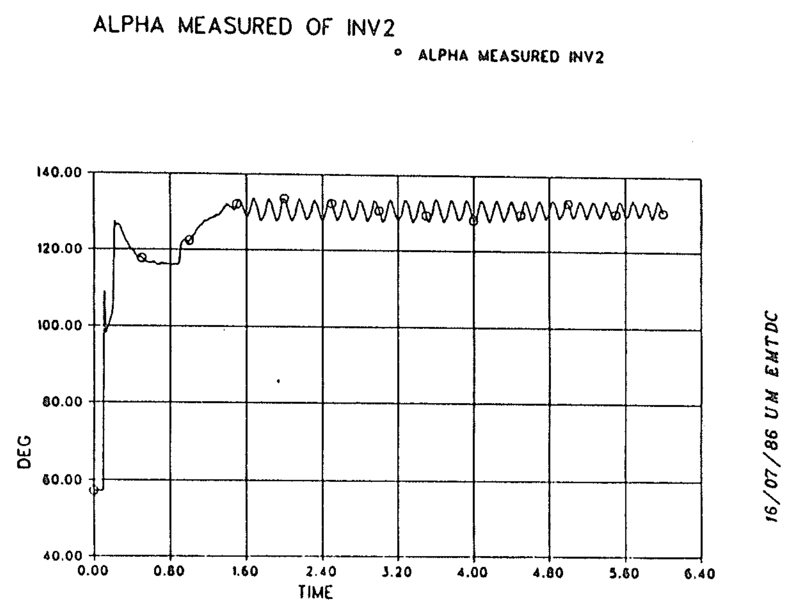

INV2 DC VOLTAGE
INV2 DC VOL
(x10³)
KV
TIME
16/07/86 UM EMTDC


DC TIE VOL
DC TIE VOL
(x10³)
DC VOL
TIME
16/07/86 UM EMTDC

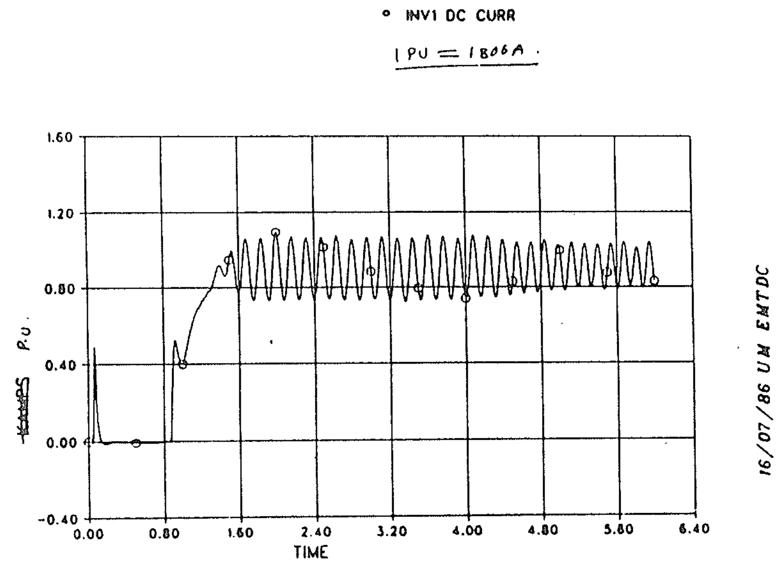

ALPHA RECTIFIER
ALPHA RECTI
DEG
TIME
16/07/86 U M EMTDC


INV1 COMM FAIL
9
T/F
TIME
16/07/86 U M EMTDC

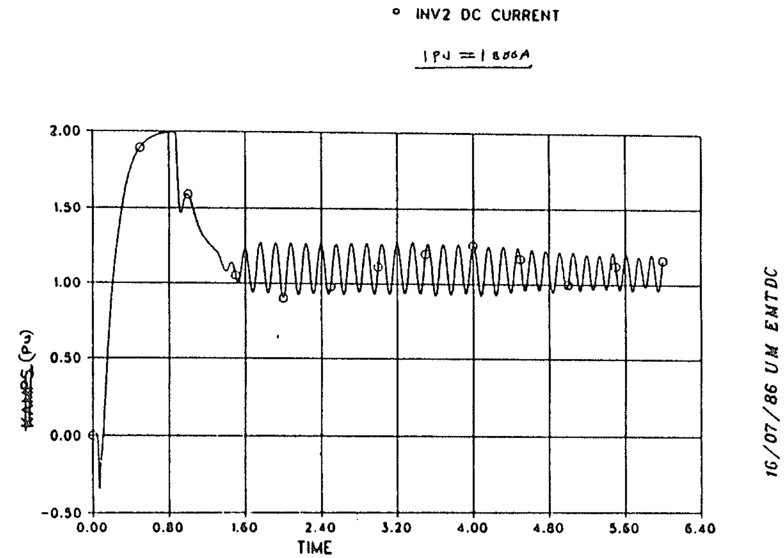

INV1 GAMMA MEASURED
INV1 GAMMA
DEG
TIME
16/07/86 U M EMTDC


ALPHA MEASURED OF INV2
ALPHA MEASURED INV2
DEG
TIME
16/07/86 U M EMTDC

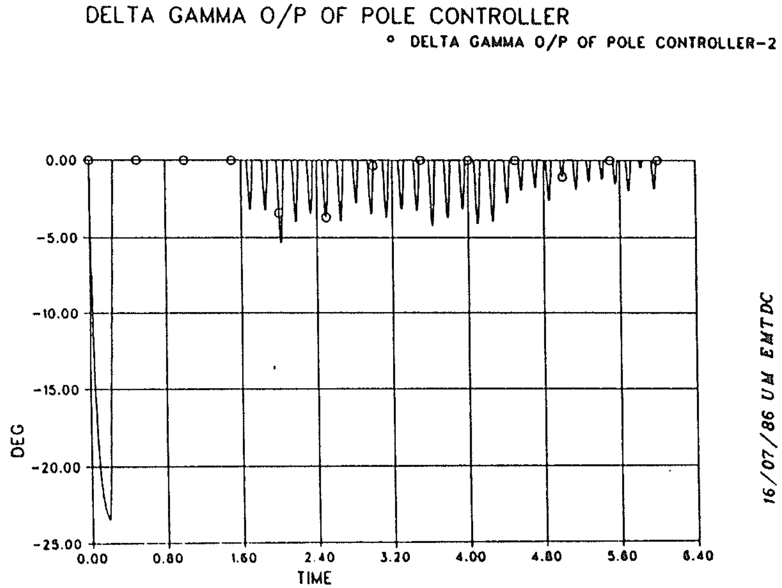
INV1 DC CURRENT



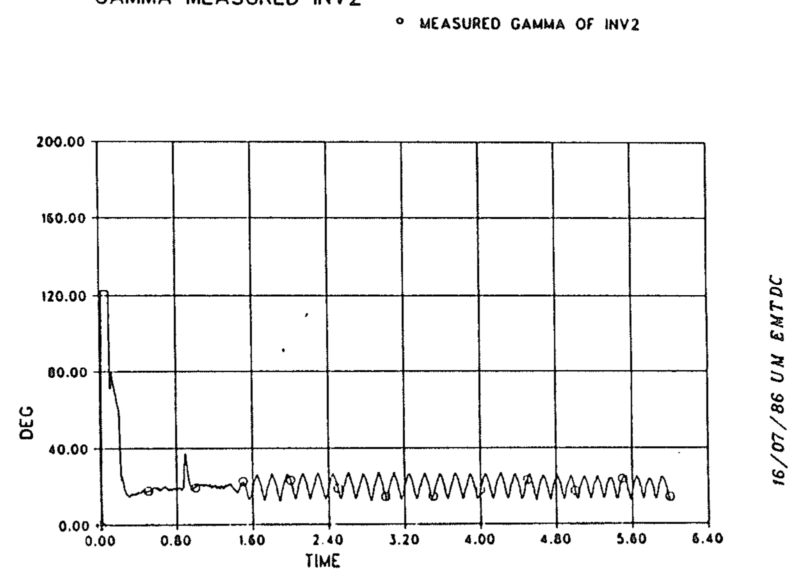
INV2 DC CURRENT



DELTA GAMMA O/P OF POLE CONTROLLER



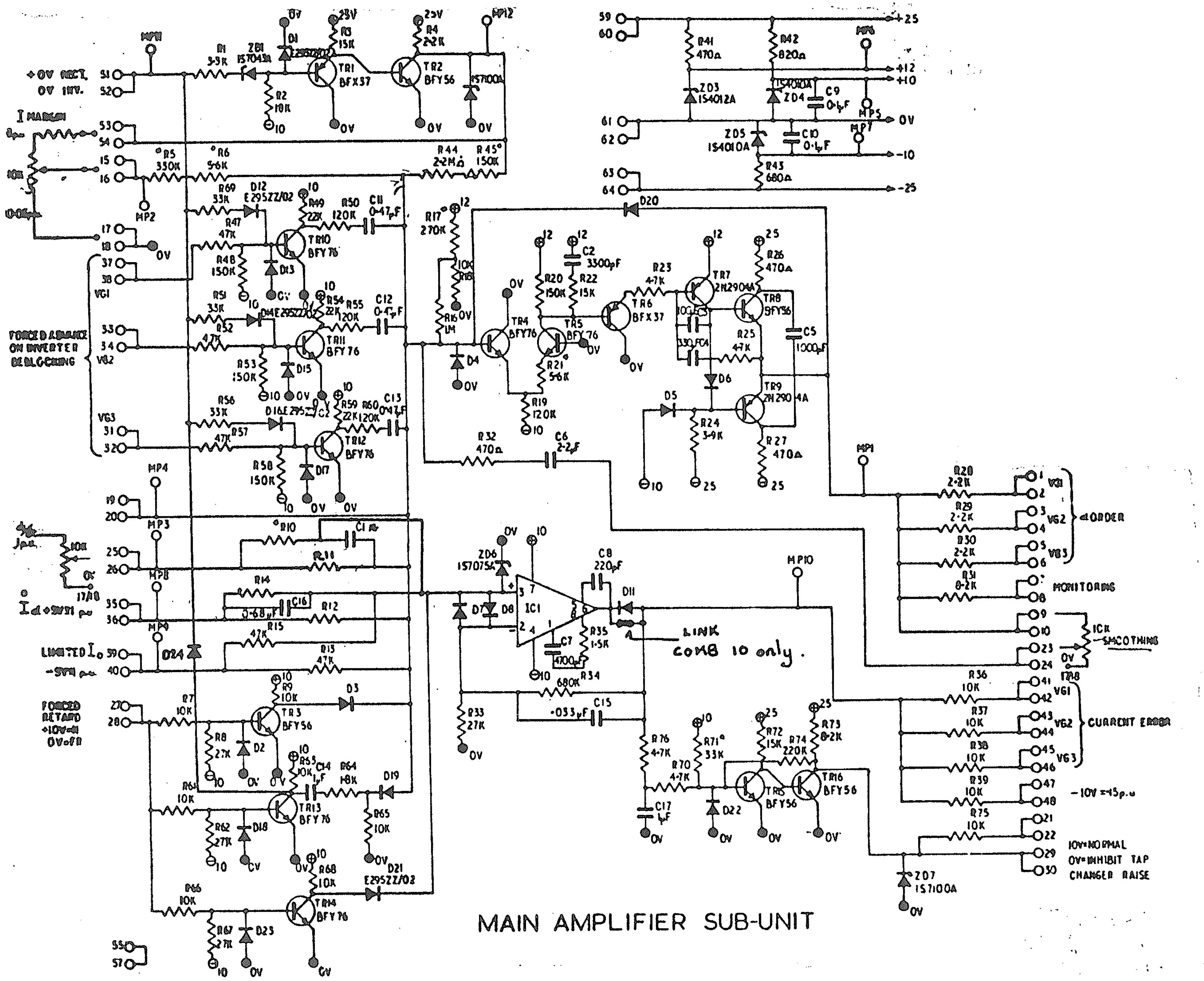
GAMMA MEASURED INV2



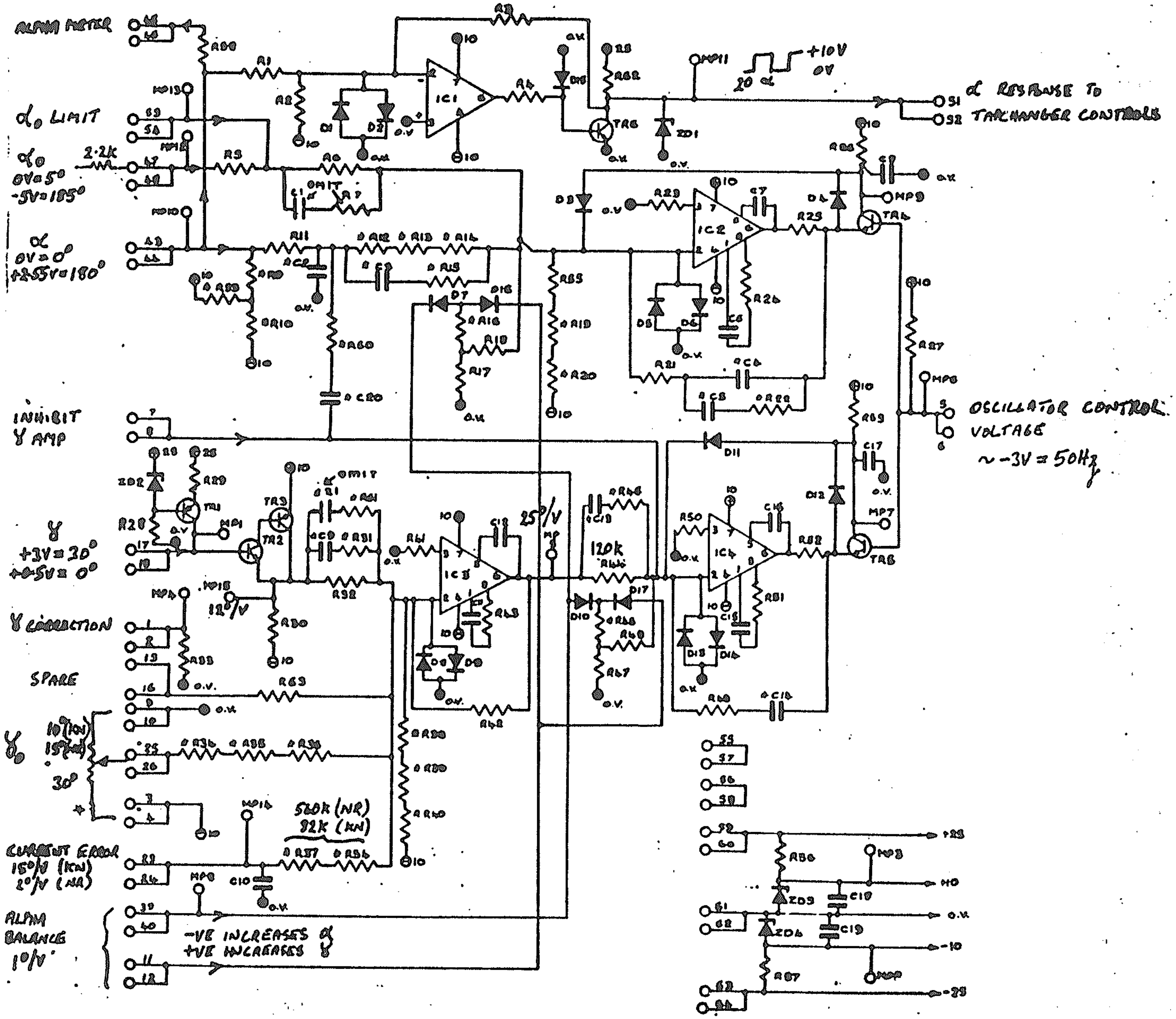
Appendix F

The following lists the bipole 1 controller drawings, which were consulted during the development of the detailed control diagram. Due to the copyright reasons, these controller diagrams could not be included here. For reference, a portion of the main amplifier, where capacitor C15 was changed, and a portion of the oscillator control circuit are included here. The interested reader is referred to Bipole1 Control Manuals for details.

1. Circuit diagram for Ring Counter, type A sub-unit DC105.
2. Circuit diagram for Ring Counter type B, sub-unit DC106.
3. Circuit diagram for Phase Limit DC107.
4. Circuit diagram for oscillator sub-unit DC108.
5. Circuit diagram for Oscillator Control, sub-unit DC109.
6. Buffer Amplifier, sub-unit DC199.
7. Main Power Controller DC184.
8. Sub-unit DC136.
9. Main Amplifier sub-unit DC135.
10. English Electric: Drawing number-S5590/0580 SHT 1&2, Interconnection for Valve Group Control Cubicle (Radisson).
11. English Electric: Drawing number-S559050909 DC current transformer connection diagram.



MAIN AMPLIFIER SUB-UNIT



CIRCUIT DIAGRAM FOR OSCILLATOR CONTROL

Appendix G

The following lists the bipole 2 controller drawings. Due to the copy right reasons, these controller diagrams could not be included here. The interested reader is referred to Bipole 2 Control Manuals for details.

1. AEG TELEFUNKEN drawing number A-029-046442 STR-3 page 70 (42347-13-401.4080) Non linear Current Controller.

2. AEG TELEFUNKEN drawing number A-029-046442 STR-3 page 106 (42347-13-401.4080) Signal From balance Controller.

3. AEG TELEFUNKEN drawing number A-029-046953 STR-3 page 29 (42347-B-401.4037) Gamma Regulator.

4. AEG TELEFUNKEN drawing number A-029-046953 STR-3 page 24 (42347-B-401.4037) Transient Reference Increase. (For Extinction Angle Controller)

5. AEG TELEFUNKEN drawing number A-029-046953 STR-3 page 14 (42347-B-401.4037) Selection of Maximum Value(Inverter Operation)

6. AEG TELEFUNKEN drawing number A-029-046953 STR-3 page 13 (42347-B-401.4037) Selection of Minimum Value (Converter Operation)

7. AEG TELEFUNKEN drawing number A-029-046953 STR-3 page 17 (42347-B-401.4037) Potentiometer and Switches.

8. AEG TELEFUNKEN drawing number A-029-046442 STR-3 page 99 (42347-B-401.4056) Input Amplifier.

9. AEG TELEFUNKEN drawing number A-029-046442 STR-3 page 121 (42347-B-401.4056) Parallel Operation- For tap changer Control.

10. AEG TELEFUNKEN drawing number A-029-046442 STR-3 page 106 (42347-B-401.4056) Signal From balance Controller.

11. AEG TELEFUNKEN drawing number A-029-046442 STR-3 page 98 (42347-B-401.4056) Input Amplifier for

    (a) Balance Control

    (b) For Line Protection

12. AEG TELEFUNKEN drawing number A-029-046442 STR-3 page 96 (42347-B-401.4056) Controlled Slope Limiter.

13. AEG TELEFUNKEN drawing number A-029-046442 STR-3 page 100 (42347-B-401.4056) Current Balance Controller.

14. AEG TELEFUNKEN drawing number A-029-046442 STR-3 page 101 (42347-B-401.4056) Power Amplifier.

15. Manitoba Hydro-Radisson station,
    Interconnection for
    Pole1 control Cubicle,PL-151 (42147-E-101.0193)