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A CONVERTER MODEL FOR THE DIGITAL SIMULATION OF TRANSIENTS IN AC/DC TRANSMISSION SYSTEMS

by

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ABSTRACT

The successful application of HVDC transmission links requires correct predictions of the performance of the dc link and the ac system to which it is interconnected. Whatever the system configuration, the steady-state, dynamic and transient behaviour of the associated dc and ac systems are mostly interdependent. To simulate these phenomena with digital computers, converter stations must be modelled in more detail than as simple dc sources.

This thesis discusses the development and implementation of a converter model which enables the converter bridge circuits to be represented in detail and the valve ignition to be controlled in the constant current mode. The model has been added to the U.B.C. Electromagnetic Transients Program to permit simulations of the complete ac/dc system. It is used to analyze the harmonics during steady-state operation, and to compare the results with those obtained from conventional (approximate) formulae. In a transient case, the new model gives closer agreement with field measurements than the simplified model used before.

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1. INTRODUCTION

Power system networks are subjected to different forms of disturbances, such as switching operations, faults, lightning surges, and other intended or unintended manual interventions. The overvoltages and currents caused by these sudden changes in circuit conditions may produce excessive stresses on the system components which must be prevented, or at least limited, to avoid potential damages. More insulation is one way of preventing excessive stresses, but there are strong economic reasons for keeping the system insulation at its lowest possible level. This can be achieved only if the transient phenomena are fully analyzed.

Extended from the idea of a-c calculating boards, the transient network analyzer (TNA) was developed for transient studies[1]. It has been widely used by the utility industry for over forty years. The system being studied is represented by actual components of reduced size and modified electrical characteristics. It is particularly useful in modelling the frequency dependent characteristics of the line constants and in those cases where the work is of exploratory nature. However, the transmission lines are approximated by cascaded π-circuits, which impose an accuracy problem as far as high-frequency components of voltage and current are concerned. Another drawback of this method is the limited access to the sophisticated equipment.

The introduction of computers has extended the scope of the mathematical modelling in solving engineering problems. Digital programming today offers a relatively easy and flexible alternative to the physical models in power system analysis. In the late 1960's, the Bonneville Power Adminis-

tration (BPA) initiated the development of the Electromagnetic Transients Program (EMTP)[2] which simulates the behaviour of the electrical system by using mathematical representations of the characteristics of the components and by solving a set of differential and algebraic matrix equations. The generalized access to computers, the flexibility of the EMTP for running cases, and the relative ease with which program changes can be made are the main reasons of its widespread acceptance. Of course, there are many areas such as frequency-dependent characteristics, nonlinearity of surge diverters, magnetic saturation of transformers, etc., which need further improvements. A combination of physical models and digital simulation can be extremely powerful and the two approaches should be seen as being complementary rather than competitive[5].

With the advent of the economic feasibility and technical applicability of HVDC transmission, there is a need for an extension of the existing facilities to carry out DC transient studies. The DC simulator uses the same control circuitry and a scaled reproduction of the commutation valves of the actual system[3,4]. When interconnected with the traditional a-c TNA, it becomes particularly valuable in development and evaluation of the control schemes. During the same period of time, considerable amount of work has been done in the field of digital simulation of HVDC systems. Additional features have also been implemented in the BPA EMTP for this purpose: a simplified model which represents the converter station as a current controlled dc voltage source[6] and a control system simulation package "TACS" (Transient Analysis of Control Systems)[7] which can accept any arbitrary interconnection of a set of control system building blocks. Good results obtained by using these two models are shown in reference papers[8,9].

The UBC Transients Program (a simpler version of the BPA EMTP)

contains only the simplified model which is inadequate for representing a combined ac/dc system. "TACS" is very flexible and can be used for a wide range of applications. However, it is relatively large and usually requires a fairly long computation time. The major research effort of this thesis has been directed towards the development of a new converter model which can be interfaced with the UBC Transients Program for HVDC simulations. The model is complex enough to analyze transients in ac/dc systems realistically enough, but it is less flexible than "TACS" inasmuch as only one particular type of converter control can be handled.

As the thesis proceeds, the implementation and testing of the model are described. New approaches in representing the limiters and the initialization process are investigated. Then the program is applied to harmonic analysis and transient studies where the comparisons with results obtained by other methods and field measurements are also included. Finally, a summary of important results and conclusions is given.

2. MODELLING AN HVDC TRANSMISSION SYSTEM

To provide accurate predictions on the preformance of an HVDC system under different operating conditions, the simulation method should be capable of representing the dc link, the associated ac systems, the converters and the controls as well. This chapter describes the main components of an HVDC system and their behaviour which the model must reflect correctly.

2.1 Network Representation

The basic components of a dc link between two ac systems are shown in Fig. 2.1. The basis for the simulation is the UBC Electromagnetic Transients Program. For convenience, it will be referred to as the "Transients Program". It is a general purpose program designed to calculate the instantaneous voltages and currents under any type of disturbance. The solution methods and its applicabilities have been well described[2,10,11]. The existing models in the Transients Program are adequate to simulate most circuit elements in both the ac and dc side networks. The dc transmission configuration can be monopolar, bipolar, ground return or metallic return. The transmission lines are represented either as multiphase π circuits or distributed constants. The ac and dc filters which comprise branches tuned to different harmonic orders of the supply frequency are represented as lumped R, L, C elements according to their connections in the system. Although zigzag winding, fork connection, polygon connection etc., are used in some commercial installations, the converter transformer can only be modelled with wye and delta connections as of now. The amount of detail in the representation of the ac systems depends on the nature of the study.

They may be represented with detailed generator and line models, or just as ac voltage sources behind Thevenin equivalent impedances.

2.2 The Converter

It is the predominant device in an HVDC system which transforms an ac voltage into a dc voltage and vice versa, controls the exchange of power between the two systems, and limits the disturbances caused by faults occurring on either side of the converting unit. The most commonly used circuit in HVDC transmission is the six-pulse bridge. Fig. 2.2 shows the basic hardware requirement. The valves can be mercury-arc valves or silicon controlled rectifiers. The valve dampers are used to avoid sudden jumps in the inverse voltage across the valves when they turn off (dv/dt protection), while the anode dampers limit the rate of rise of current during valve ignition (di/dt protection).

The performance of a converter bridge is controlled by changing the firing angle, α, of the valves. Fig. 2.3 shows how the dc voltage is effected by variations in α. As α exceeds 90°, the bridge changes from rectification operation to inversion operation. To minimize the generation of harmonics, the bridge units are usually paired with wye/wye and delta/wye transformers, with a phase shift of 30° between them, to form a 12-pulse unit. These 12-pulse units are themselves connected in series to produce the required transmission voltage level.

To simulate the operation of the valves, the existing model of a diode switch, which conducts whenever the anode voltage is higher than the cathode voltage and interrupts at current zero, is modified so that the ignition is controlled by an external firing signal. The characteristics of

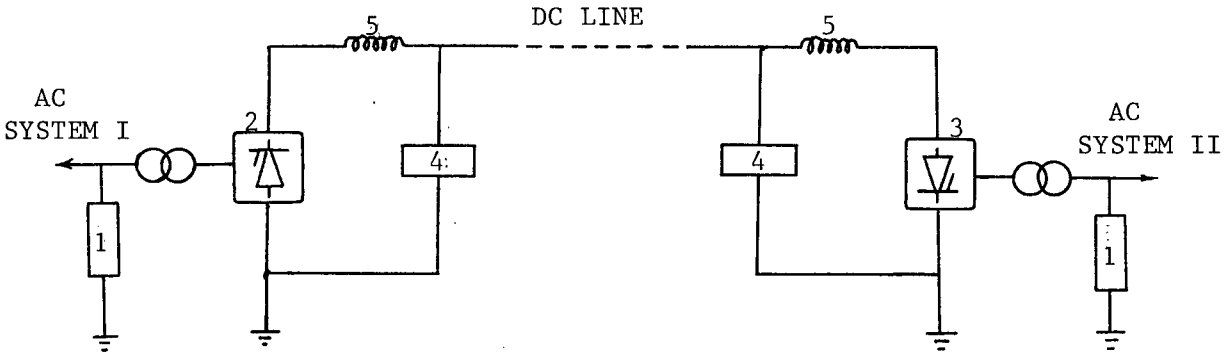


Fig. 2.1 Basic HVDC Link: 1 - AC filters; 2 - Rectifier station; 3 - Inverter station; 4 - DC filters; 5 - DC reactors.

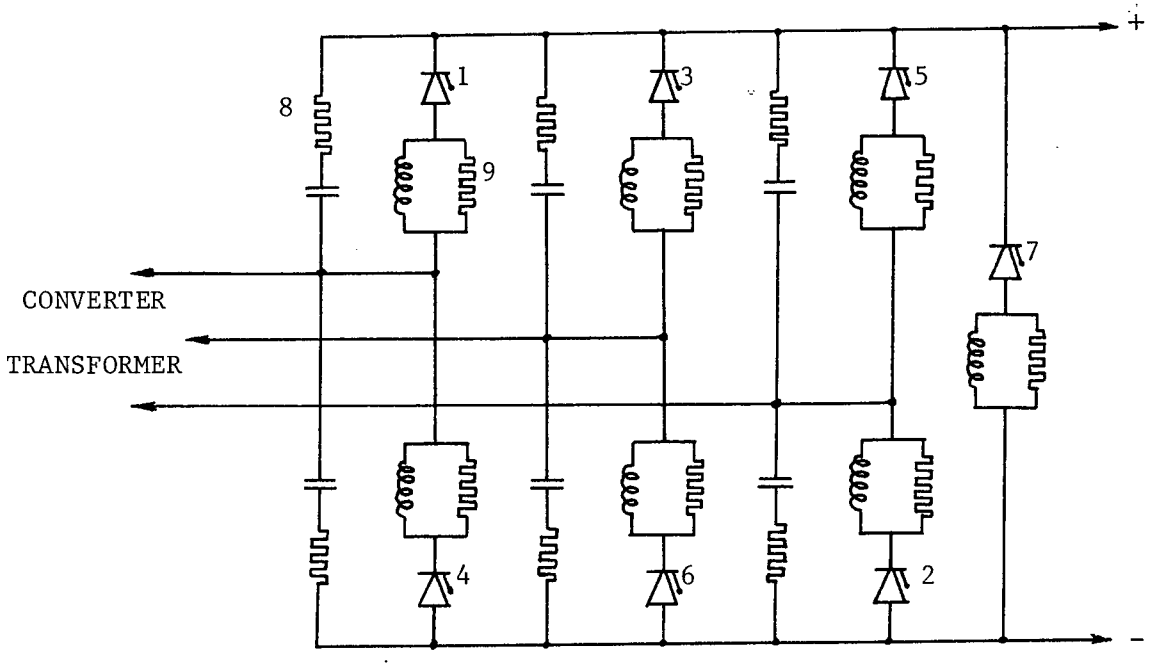


Fig. 2.2 Basic Hardware of a converter bridge: 1 to 6 - Main valves; 7 - Bypass valve; 8 - Valve damper; 9 - Anode damper.

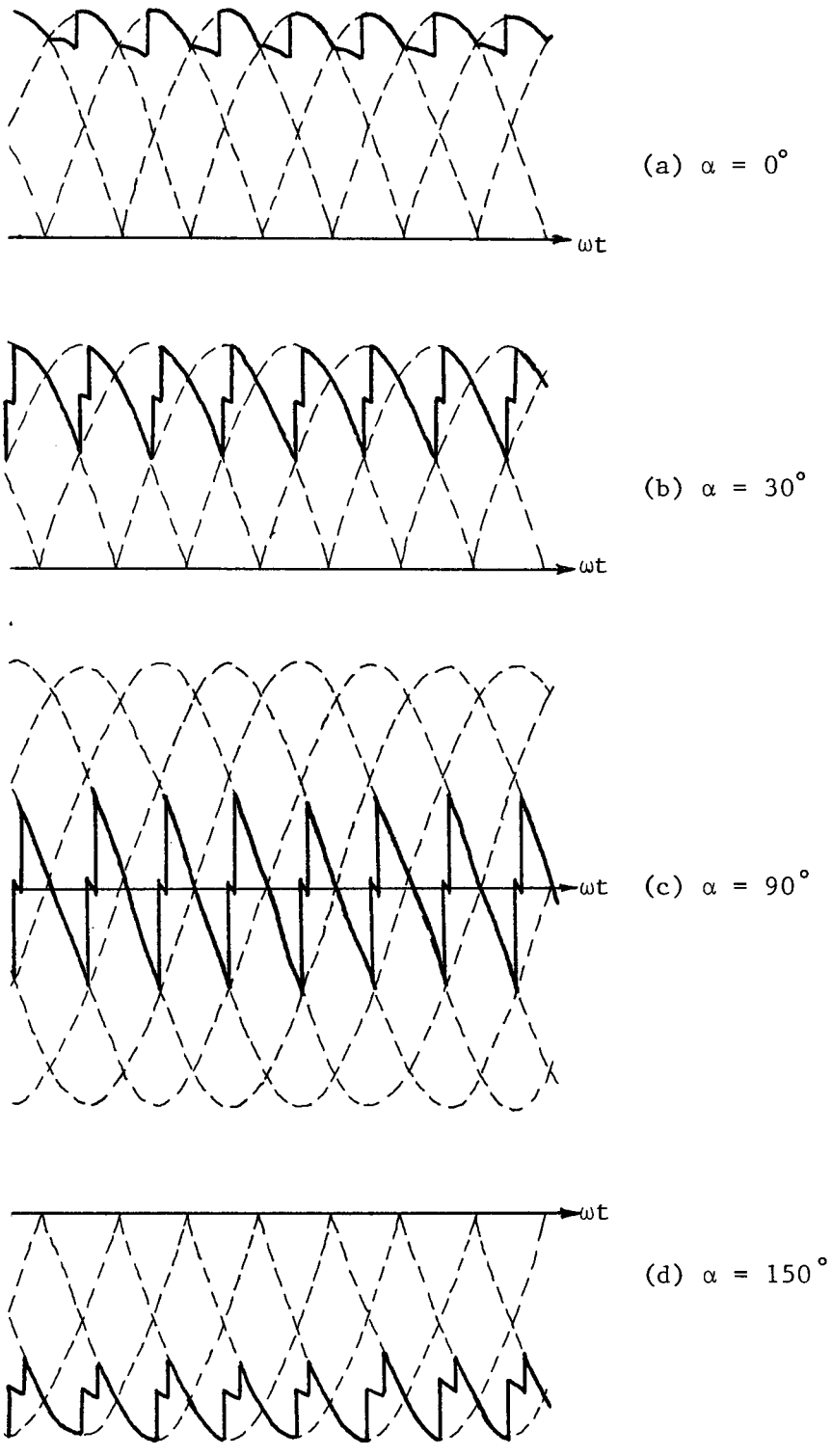


Fig. 2.3 Direct voltage (heavy lines) of bridge converter with variation of ignition delay angle α : (a),(b) - Rectification; (c) - Zero voltage; (d) - Inversion.

the control systems and the generation of the firing pulses will be described in the next section.

2.3 Converter Control Characteristics

The control loop of rectification is generally a constant current loop[12]. The schematic diagram of the basic components of such a controller is shown in Fig. 2.4. Recent installations contain additional and more sophisticated schemes, such as constant power order, dc power modulation or frequency modulation for ac system damping, etc. These latter applications are extensions of the former and the variables under control are ultimately converted into changes of current order. For electromagnetic transients analysis, the constant current controller plays the most significant part. Therefore, to simplify the modelling, only this control scheme is implemented in the program.

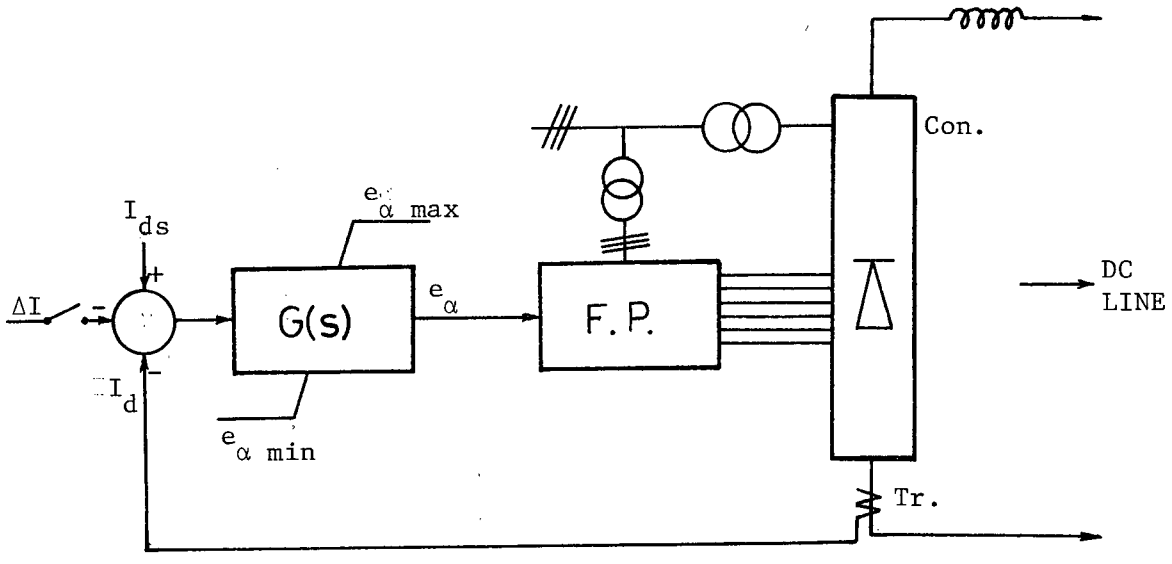


Fig. 2.4 Constant Current Controller : I_{ds} current command; Id line current ; ΔI current margin; G(s) regulator transfer function ; e_{α} regulator output; e_{α} max, e_{α} min limits of regulator; Con. converter; F.P. firing pulse generation; Tr. transductor.

The control characteristics may be divided into three sections[13,14] (Fig. 2.5): (1) Constant minimum ignition angle (C.I.A.) control is used to keep the rectifier operating with its minimum permissible firing delay α_0. The theoretical minimum α_0 equals zero, but in practice it is kept to between 10° to 20° in order to maintain an adequate margin for rapid increases in rectifier voltage. The slope of the curve in this section depends upon the value of commutating reactance; the output voltage of the converter is given by,

$$V_d = V_{do} \cos \alpha_0 - \frac{3}{\pi} X_c I_d \qquad (2.1)$$

where V_d = average converter voltage,

V_{do} = converter ideal no-load direct voltage,

α_0 = minimum delay angle,

X_c = commutating reactance per phase,

I_d = dc line current.

(2) Constant Current (C.C.) Control is used to provide both the rectifier and inverter with the control ability to regulate the line current when it does not agree with a set reference I_{ds}. The slope of the curve depends mainly on the output of the current regulator, and the output voltage is given by,

$$V_d = V_{do} \cos \alpha - \frac{3}{\pi} X_c I_d \qquad (2.2)$$

where α = angle of delay of firing.

(3) Constant Extinction Angle (C.E.A.) Control is used to keep the inverter operating at its minimum extinction advance angle. The angle must be kept small to provide high power factor but large enough to maintain a safe margin to prevent commutation failures. The slope of the curve again depends on the value of the commutating reactance, and the output voltage of the converter is given by

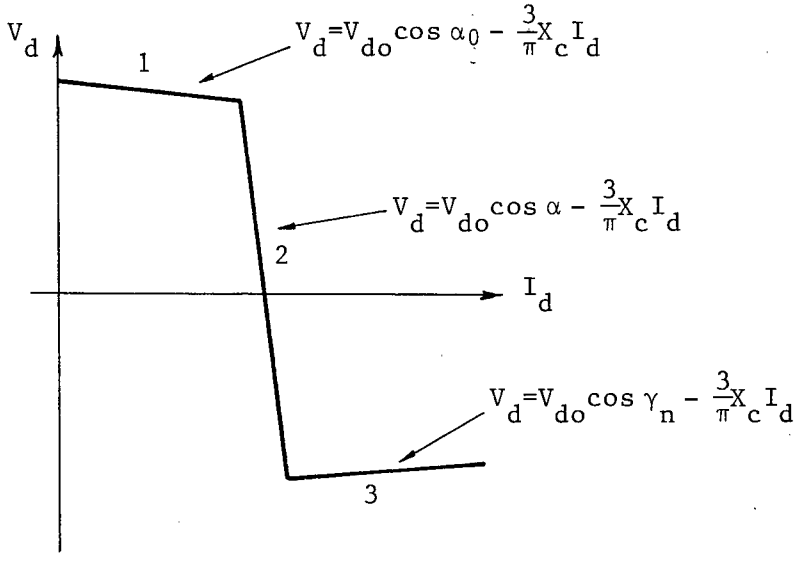


Fig. 2.5 Control Characteristic of Converter: 1 - C.I.A. control; 2 - C.C. control; 3 - C.E.A. control.

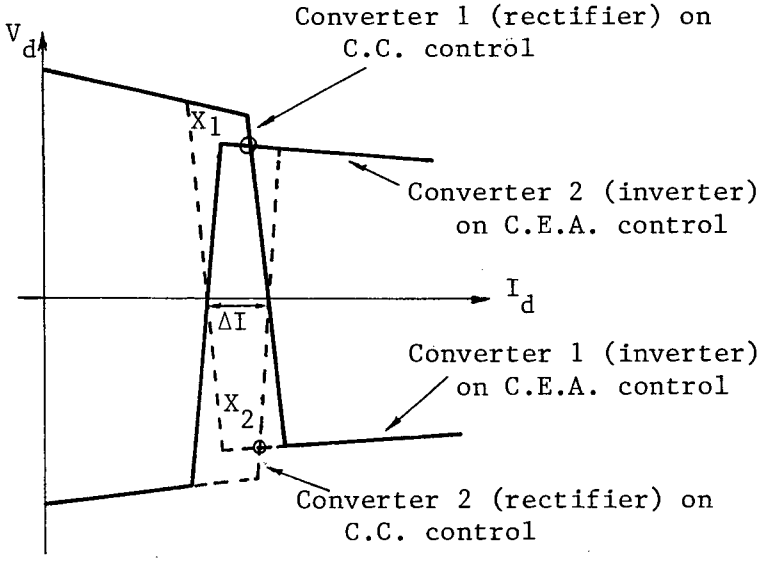


Fig. 2.6 Two-converter Control Characteristic.

$$V_d = V_{do} \cos \gamma_n - \frac{3}{\pi} X_c I_d \tag{2.3}$$

where γ_n = minimum extinction advance angle.

For a two-converter system, the operating point is at the intersection of the two control characteristics. In Fig. 2.6, the intersection X_1 between the solid lines is the operating point where converter 1 is at constant current mode and converter 2 at constant extinction angle mode. Power is transmitted from converter 1 to converter 2. If a reversal of power transmission is necessary, the characteristics are changed to those shown by the broken lines and X_2 will become the operating point. The difference between the current settings I_{ds_1} and I_{ds_2} of the two converters is called the current margin, ΔI. This margin, typically 15% of the rated current, has to be large enough to avoid the two converters from operating at the steep constant-current lines simultaneously. Such operation is undesirable and may also be very unstable.

The operating mode of a converter is determined by the control amplifier output voltage e_α. As seen from Fig. 2.4,

$$e_\alpha(s) = (I_{ds} - I_d - \Delta I)\, G(s) \tag{2.4}$$

The parameters of the transfer function G(s) can be obtained from the station operating manuals[15]. The transfer function of the control scheme studied in this thesis is a second order one of the form

$$G(s) = \frac{K(1+sT_2)}{(1+sT_1)(1+sT_3)} \tag{2.5}$$

where K is the static gain

and T_1, T_2, T_3 are time constants.

The other settings depend on the operating conditions of the system. Different amplifier output voltages lead the converter to different operating regions:

a) if $e_{\alpha\ max} > e_{\alpha} > e_{\alpha\ min}$, the converter operates in region '2' (see Fig. 2.5), i.e. on C.C. Control.

b) if $e_{\alpha} < e_{\alpha\ min}$, the converter operates in region '3', i.e. C.E.A. Control.

c) if $e_{\alpha} > e_{\alpha\ max}$, the converter operates in region '1', i.e. C.I.A. Control.

As shown in Fig. 2.7, the direct voltage V_d is a function of e_{α} and can be described as[6]:

$$V_d = k_1 + k_2\ e_{\alpha} \tag{2.6}$$

where k_1 = intercept,

k_2 = slope of the converter constant current control characteristic.

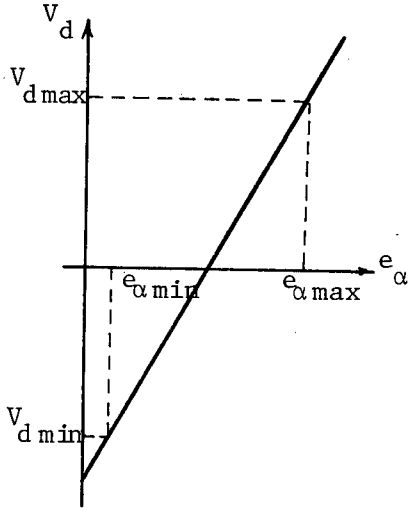


Fig. 2.7 Relationship between D.C. voltage V_d and regulator output e_{α}

Knowing the value of V_d and the operating region of the converter, the delay angle α can be calculated from equations 2.1, 2.2 or 2.3. Then the pulse generator determines the firing instant for each valve. There are two basic approaches in the design of pulse generators:

1) Individual phase control: Six independent delay circuits time the firing pulse of each valve. The delay is calculated from the earliest instant at which firing is possible, that is, the instant at which the commutating voltage becomes positive. This type of control has the advantage that it can achieve the highest possible direct voltage with the asymmetry prevailing at the time. However, it has a drawback inasmuch as abnormal harmonics, especially of the third order, appear in the currents.

2) Equidistant firing control (or 'equal space' control)[16]: There is always one reference phase at which the firing angle is determined according to the control amplifier output. Starting with this angle, each firing pulse is timed at 60° electrical after the preceding pulse, that is, the valves are ignited at equal time intervals. As a result, abnormal harmonics are suppressed but the response in the event of a fault is slower.

3. IMPLEMENTATION OF THE CONVERTER MODEL

This chapter describes the solution method and the computer implementation of the converter model. Also included is a discussion of the two major problems encountered during the implementation.

3.1 Subroutine VALCON

To simulate the converter control of the HVDC system, a subroutine VALCON ("Valve Control") was developed. The FORTRAN listing of the program is included in Appendix 1.

Input Requirements The user must provide the following information, in addition to the usual input data of the Transients Program:

1) The coefficients of the transfer function K, T_1, T_2, T_3,
2) the operating mode of the converter, i.e. rectification on inversion,
3) the initial operating region on the converter control characteristic,
4) the commutating reactance X_c,
5) the electrical frequency,
6) the connection of the converter transformer, i.e. wye-wye on wye-delta,
7) identification of a branch (usually a switch) where the reference direct current will be taken from,
8) three node names on the primary side of the converter transformer from which the commutation voltage of each valve will be calculated,
9) the limits $V_{d\ max}$, $V_{d\ min}$, that are placed on the excursions of the regulator amplifier,
10) the pulse generator type.

Numerical Integration The s-domain equation (2.4) can be expressed as two first order differential equations:

$$X(t) = \frac{d\, e_\alpha(t)}{dt}$$

$$e_\alpha(t) + T\, X(t) + P \frac{dX(t)}{dt} = KI(t) + KT_2 \frac{dI(t)}{dt} \qquad (3.1)$$

where

$$I(t) = I_{ds} - I_d - \Delta I$$

$$T = T_1 + T_3$$

$$P = T_1 \cdot T_3$$

These equations, as described in more detail in the next section, represent the converter control loop when the regulator amplifier operates within the limits. They must be solved simultaneously with the rest of the external electric network. The numerical integration formula based on the trapezoidal rule was adopted in the program. This algorithm was chosen, firstly because it is the simplest second order implicit method and is numerically stable for any stepsize Δt[17]; secondly, it simplifies the interfacing problem as the Transients Program uses the same stepsize and integration technique. Applying the trapezoidal rule to equation (3.1) results in the algebraic difference equations

$$X(t) + X(t-\Delta t) = \frac{2}{\Delta t} [e_\alpha(t) - e_\alpha(t-\Delta t)]$$

$$\frac{1}{2} [e_\alpha(t) + e_\alpha(t-\Delta t)] + \frac{T}{2} [X(t) + X(t-\Delta t)] + \frac{P}{\Delta t} [X(t) - X(t-\Delta t)] \qquad (3.2)$$

$$= \frac{K}{2} [I(t) + I(t-\Delta t)] + \frac{T_2 K}{\Delta t} [I(t) - I(t-\Delta t)]$$

Rearranging terms, this becomes

$$e_\alpha(t) = \frac{B}{A} I(t) + HIST\ (t-\Delta t)$$

$$X(t) = \frac{2}{\Delta t} [e_\alpha(t) - e_\alpha(t-\Delta t)] - X(t-\Delta t) \qquad (3.3)$$

where

$$A = 1 + \frac{2T}{\Delta t} + \frac{4P}{(\Delta t)^2}$$

$$B = K(1 + \frac{2T_2}{\Delta t})$$

and the "history" of the state of the amplifier

$$HIST\ (t-\Delta t) = \frac{2K-B}{A} I(t-\Delta t) + \frac{A-2}{A} e_{\alpha}(t-\Delta t) + \frac{4P}{A \cdot \Delta t} X(t-\Delta t)$$

After the program enters the time-step loop, the instantaneous values of e_{α} and X are calculated and the history term is updated at each step. Then the delay angles and the firing pulses are determined based on the equations described in the previous chapter.

The Interface The electric network and the control system are solved separately in the Transients Program and in the subroutine VALCON, respectively. Variables such as ac bus voltages, dc line currents, valve status (open or close) etc., are passed from the main program to VALCON, which, after manipulation through its logic, returns the appropriate firing signals to continue the simulation. Modifications in the Transients Program to incorporate this interface are documented in Appendix 2 and a general flow chart of the simulation algorithm is shown in Fig. 3.1.

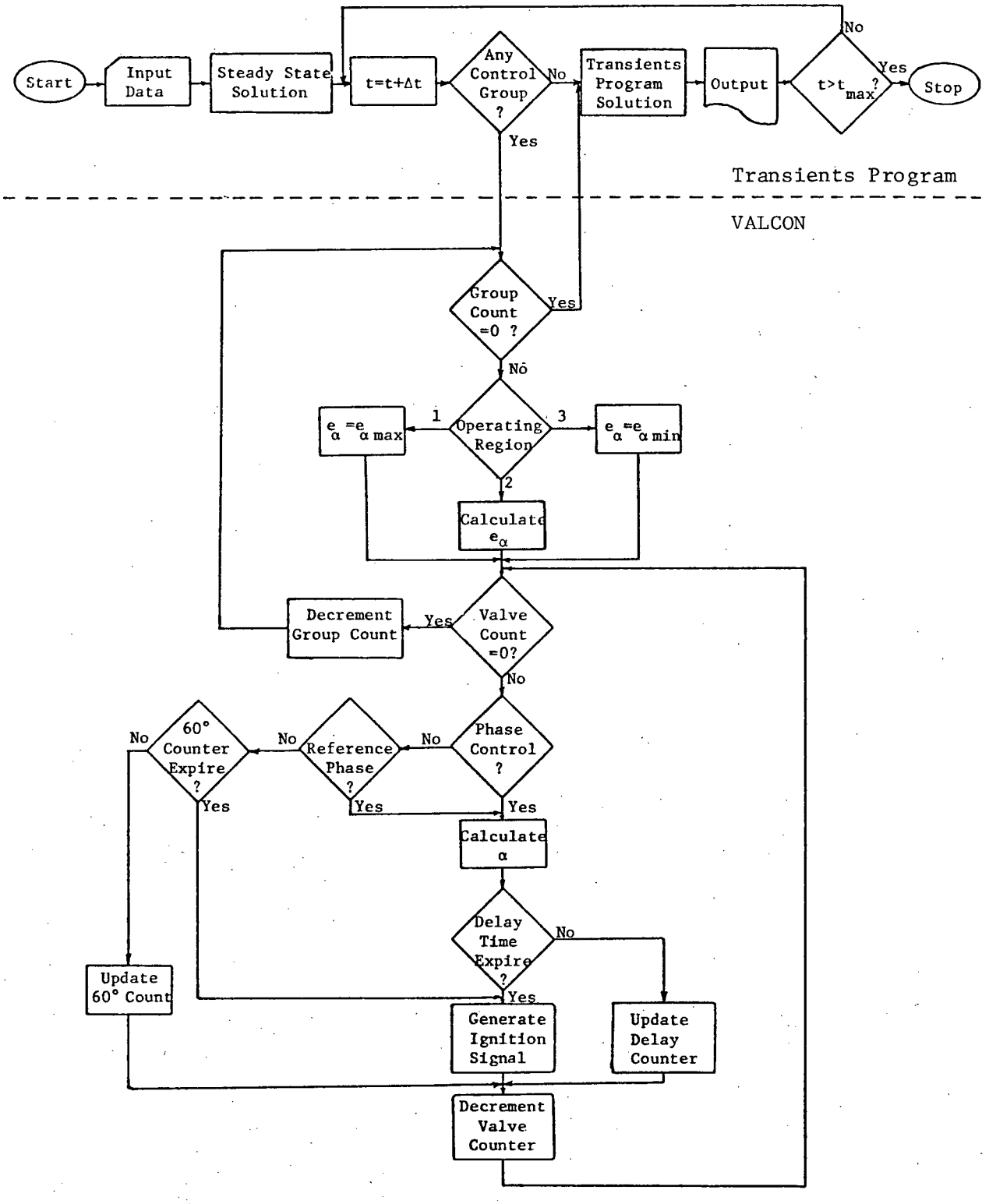


Fig. 3.1 Flow Chart of the Simulation.

3.2 Limiter Representation

The control amplifier output is usually clamped according to the maximum and minimum angle of delay constraints of the converters. This type of limiter creates a special problem of nonlinearity. The solution method which has been used in the existing simplified model is such that the derivatives of the output are set to zero[7] when a limit is reached, which changes the structure of the differential equations. To investigate the validity of this representation, the actual hardware arrangement of the control circuit must be analyzed. Assuming that all the transducers and filters are ideal, and neglecting all the protective circuits and monitoring devices, the control amplifier circuit is shown in Fig. 3.2. The overall relationship between the input and output voltage is[18]:

$$\frac{e_\alpha}{e_i} = -\frac{Z_0}{Z_i} \tag{3.4}$$

where Z_0 = short-circuit transfer impedance function of the feedback loop

Z_i = short-circuit transfer impedance function of the input circuit.

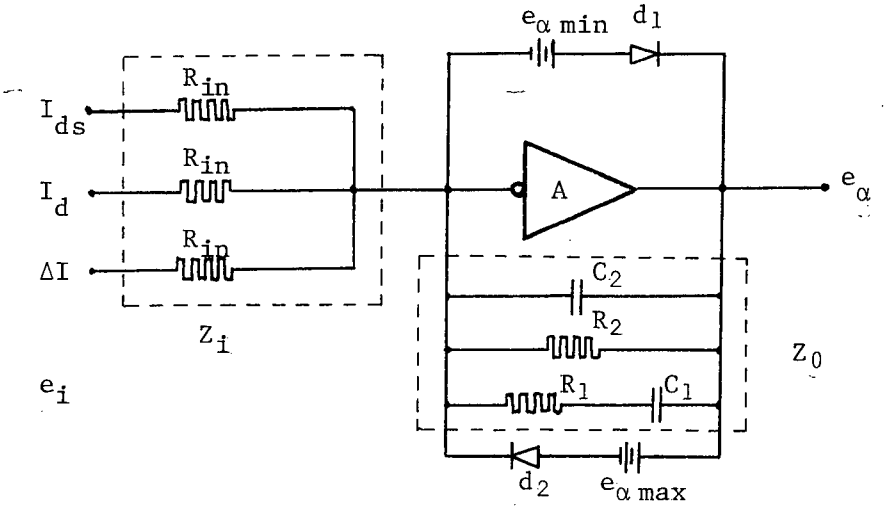


Fig. 3.2 Control Amplifier Circuit. A High Gain Amplifier; C, R's Capacitance and Resistance of the Damping Circuit; e_i, e_α Input & Output Voltages; d_1, d_2 clamping diodes.

The input transfer impedance Z_i is simply R_{in}, and the complex transfer impedance of the RC feedback network in terms of the Laplace-transform operator S is in the same form as equation (2.5) with the time constants having the relationships given by[19]

$$\begin{aligned} T_2 &= R_1 C_1 \\ T_1 \cdot T_3 &= R_1 R_2 C_1 C_2 \\ T_1 + T_3 &= R_1 C_1 + R_2 C_2 + R_2 C_1 \end{aligned} \tag{3.5}$$

The function of the control amplifier can be divided into three different operating regions. Fig. 3.3 shows that in each region, the current relationship should be described by different differential equations:

a) $e_{\alpha\,min} < e_\alpha < e_{\alpha\,max}$ i.e. the amplifier is in its active region. e_α varies as the input current i_1 changes, the equation of the system

$$e_\alpha(t) = - Z_0(t)\, i_1(t) \tag{3.6}$$

b) $e_\alpha = e_{\alpha\,min}$ i.e. the amplifier is clamped to prevent it from going negative or less than minimum. The diode d_1 is conducting and the output is kept at $e_{\alpha\,min}$. When the amplifier is driven to the limit, the circuit will undergo a transient period which can be described by the equation

$$e_{\alpha\,min} = Z_0(t) \cdot [i_2(t) - i_1(t)] \tag{3.7}$$

The amplifier comes out of the clamping condition when I_d becomes less than $(I_{ds} - \Delta I)$.

c) $e_\alpha = e_{\alpha\,max}$ i.e. the amplifier goes into saturation or to a clamped value of maximum output. Diode d_2 is conducting and the equation under this condition is

$$e_{\alpha\,max} = Z_0(t)\, [i_2(t) - i_1(t)] \tag{3.8}$$

The amplifier comes out of this region when I_d becomes greater than $(I_{ds} - \Delta I)$.

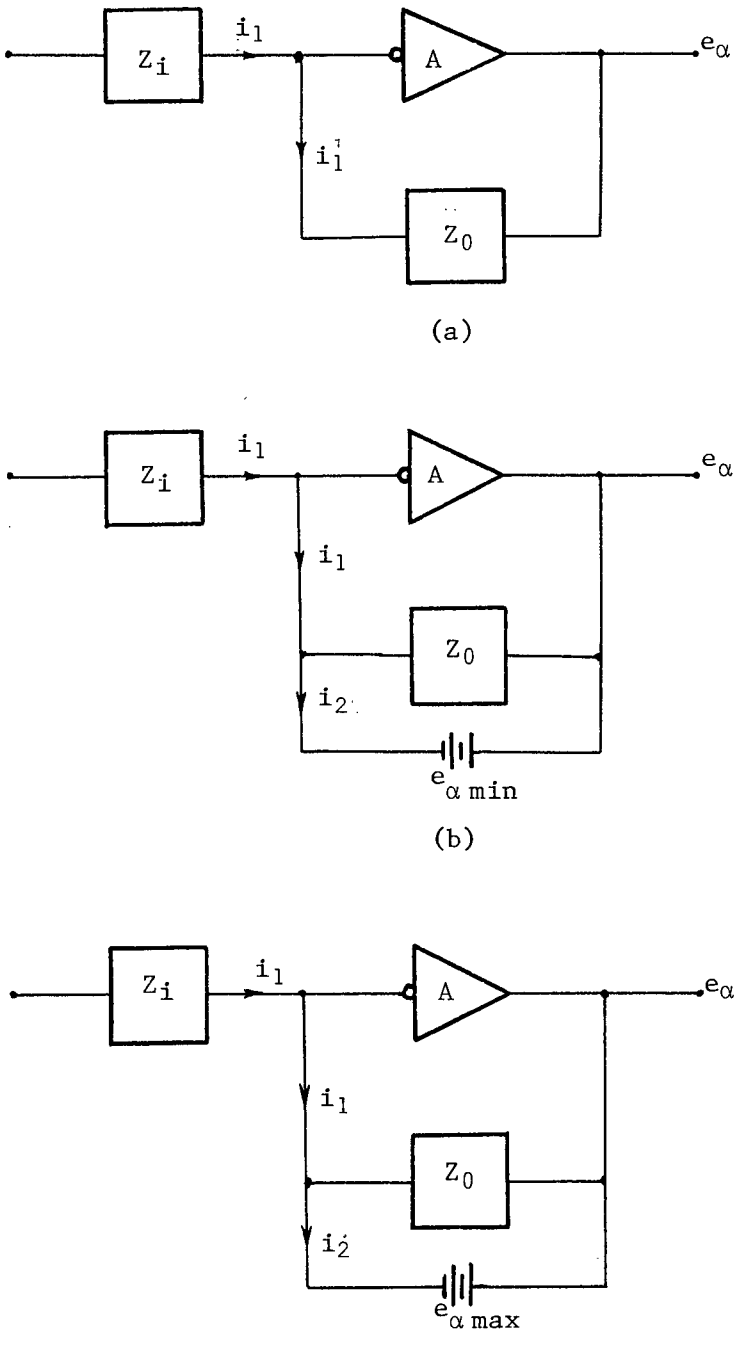


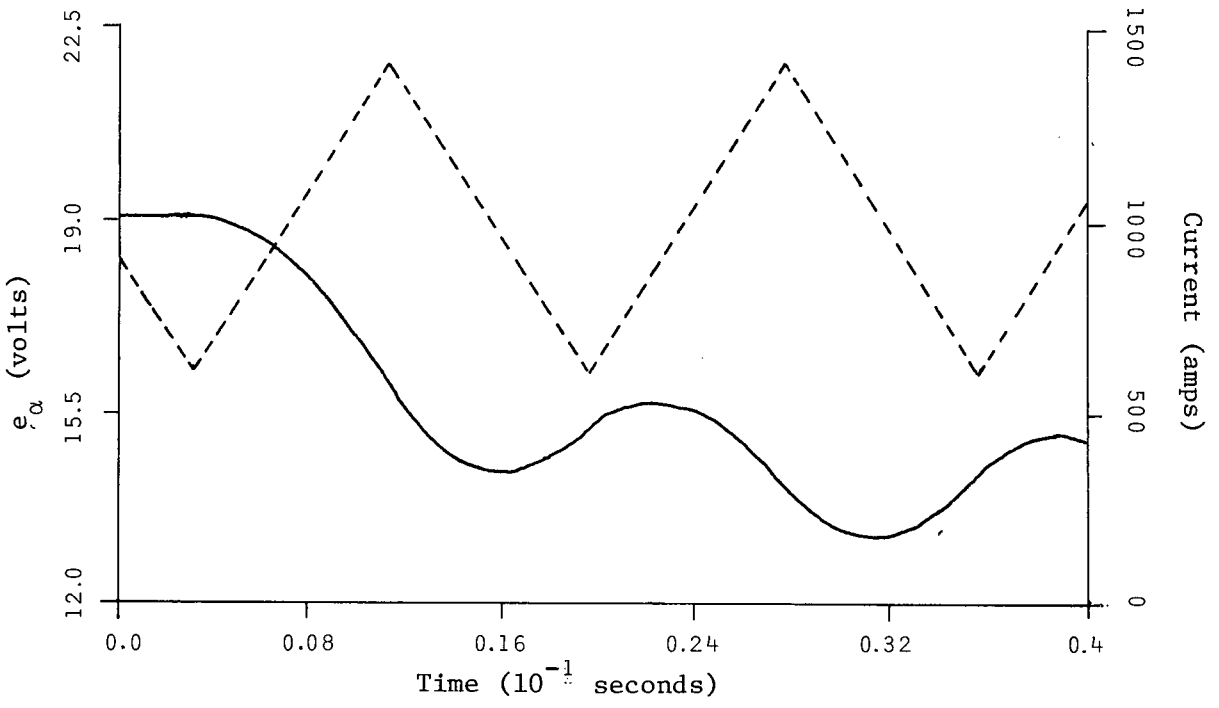
Fig. 3.3 Three Operating Regions of the Control Amplifier: (a) - in active region; (b) - clamped to minimum value; (c) - clamped to maximum value.

To simulate the behaviour of the amplifier accurately, all these three equations must be included. Every time the subroutine is called, the operating region of the amplifier is determined and the mathematical solution will be switched from one equation to another whenever the operating region is changed.

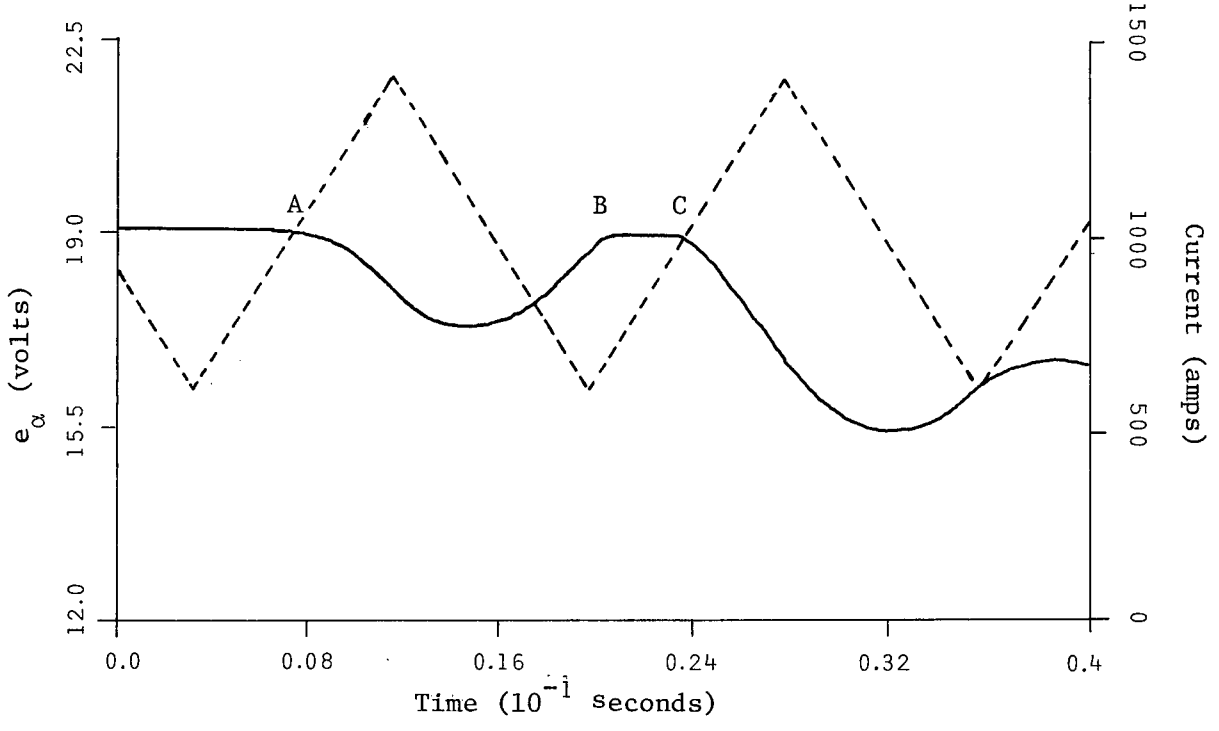
The previously used method of setting the derivatives equal to zero at the limit gives erroneous simulation results, especially when the system is subjected to disturbances which drive the amplifier in and out of the limit in short time intervals. To illustrate the difference between the two approaches, a simple control scheme, as shown in Fig. 2.4, was simulated with

$$G(s) = \frac{1.39\ (1 + 4.4s)}{(1 + .04s)(1 + .0103s)}$$

and I_{ds} = 900 Amp., ΔI = -100 Amp. $e_{\alpha\ max}$ = 18.9 volt.
The converter operated in the upper limit in steady state and was subjected to a saw-tooth disturbance. Since $I_{ds} - \Delta I$ = 1000 Amp., the amplifier is expected to stay in the upper limit until the input current exceeds this value. Fig. 3.4(a) shows that the amplifier jumps out of the limit prematurely with the previously used approach, and thus cannot return to the limit again in the subsequent fall-off of the input current. The method of solving different differential equations according to the operating regions of the amplifier gives a more accurate simulation. Fig. 3.4(b) also shows that the amplifier responds differently depending on whether the amplifier has stayed in the limit long enough to reach its steady state: At A, the amplifier jumps out of the limit after the damping circuit reaches the steady state, while at C, the damping circuit is still in the transient process after the amplifier switches into the limit at B.



(a) First Approach : setting derivatives to zero when output hits the limit.



(b) Second Approach : solving different differential equations according to the operating regions of the amplifier.

Fig. 3.4 Response of the current regulator when subject to a saw-toothed disturbance : —— amplifier output; - - - - current input.

3.3 Initialization

Typical transient studies start with the electric network being in its steady state conditions. While it is always possible to ramp the simulation up to steady state, this not only requires additional computer time, but also skill on the side of the user. It is therefore desirable to initialize the network variables to their steady-state values as closely as possible. The present version of the Transients Program has a subroutine which automatically calculates the ac steady state solution for a single source frequency. In addition, it has an option to read in user-specified initial data, which will override automatically computed values. The initialization process in the simulation of ac/dc system is complicated by the fact that such systems have two or more fundamental frequencies as well as harmonics, and that the converter valves create a discontinuity between the ac and dc components. Neither option mentioned is therefore adequate to handle the initialization alone. To solve the problem, a combination of the two features has been used.

At time $t < 0$, a typical system, as shown in Fig. 3.5, can be partitioned into three separate groups: The power transmitting ac system, the dc link, and the power receiving ac system. The converter bridges serve as the boundaries, and all the valves are assumed in open state at $t < 0$. With the ac networks disconnected from the dc system, dc voltages (simulated as ac sources of very low frequencies and amplitudes equal to the dc operating voltages) are inserted at the terminals of the dc line. AC sources are used because the steady-state subroutine can only handle ac steady-state solutions, since at dc, admittances of inductive branches would become infinite. Practice has shown that with a frequency of $f = 10^{-3}$ Hz, the ac solution is sufficiently close to the dc solution[14], and reactances ωL and susceptances ωC

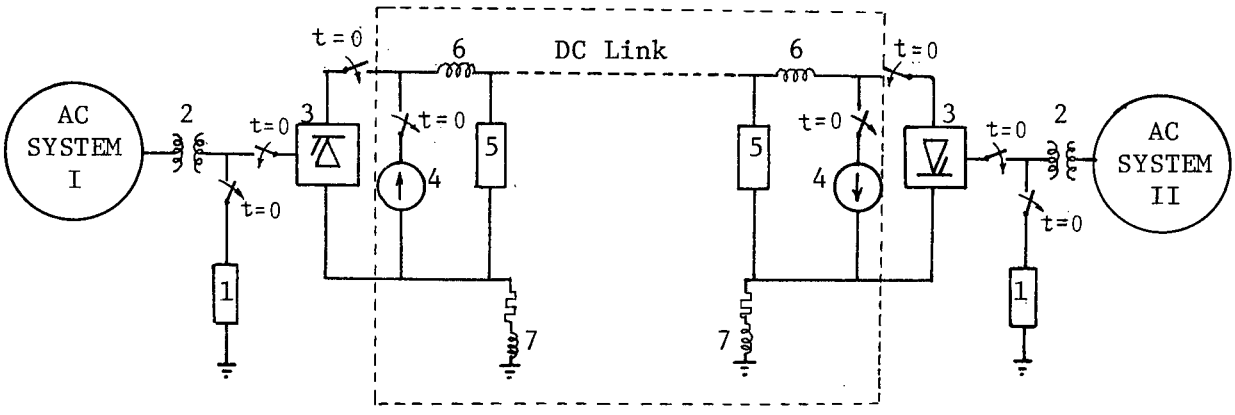


Fig. 3.5 System set up for initialization: 1 - Equivalent load; 2 - Converter transformer; 3 - Converter station; 4 - AC current source with very low frequency; 5 - DC filters; 6 - Smoothing reactor; 7 - Electrode line.

are still large enough to avoid numerical problems. This approach gives good dc steady state solution for the dotted area in Fig. 3.5, with all the harmonic components neglected.

To properly initialize the ac portions of the system, the dc network is represented as an equivalent load connected to each leg of the secondary windings of the converter transformers. The initial dc operating conditions, such as dc terminal voltages and currents, can be obtained from load flow studies, and with losses in the converter stations neglected, ac power equals dc power. The equivalent load, which will be a positive or negative impedance depending on whether the converter operates as rectifier or inverter, can be estimated from

$$Z_{eq} = \frac{V^2}{3S^*} \tag{3.9}$$

where V = the rms line-to-ground alternating voltage

S* = the conjugate of the apparent power.

With this load connected at $t < 0$, the initial conditions of the two ac systems are computed by the steady-state subroutine.

At $t = 0$, the equivalent loads are switched off and the ac and dc networks are reconnected through the valves. The dc steady-state initial

conditions are set through the read-in option, and with subroutine VALCON, determining which valves must be ignited, the system is virtually at its normal operating state and ready for the transient simulation for $t > 0$. Fig. 3.6 shows a simulation over a time span of 75 ms for a case of a six-pulse converter operation with both ac and dc filters. The system settles down very fast. Simulations with the order of dc and ac steady state solutions reversed were also studied and the results were basically identical. It is therefore reasonable to assume that harmonics can be ignored in the initialization.

Other researchers have found that ac/dc system simulations are very sensitive to wrong initial values[12]. One concern in the method described here is the behaviour of the valve dampers. Since the circuits in the converter bridge are disconnected during the computation of the steady-state solution, they are subjected to wrong initial conditions when the simulation starts at $t = 0$. Two cases were simulated: one with the simulation starting at the middle of the non-commutation period, i.e. the valve dampers are quiescent; the other with the simulation starting at a point of commutation, i.e. the valve dampers are in a transient state. The resulting curves in Fig. 3.7 show no differences after one sixth of a cycle. The exclusion of the valve dampers in the initialization process does not seem to cause noticeable disturbances.

However, improper initialization on any part of the dc line may give inaccurate results or even lead to wrong firing sequences. Fig. 3.8 illustrates the severity of this problem. The system studied previously is initialized in the same way except that the electrode line, which is simply modelled as a lumped R-L branch, was not included in the initialization, i.e. it had zero initial values. The curves show an erroneous high voltage

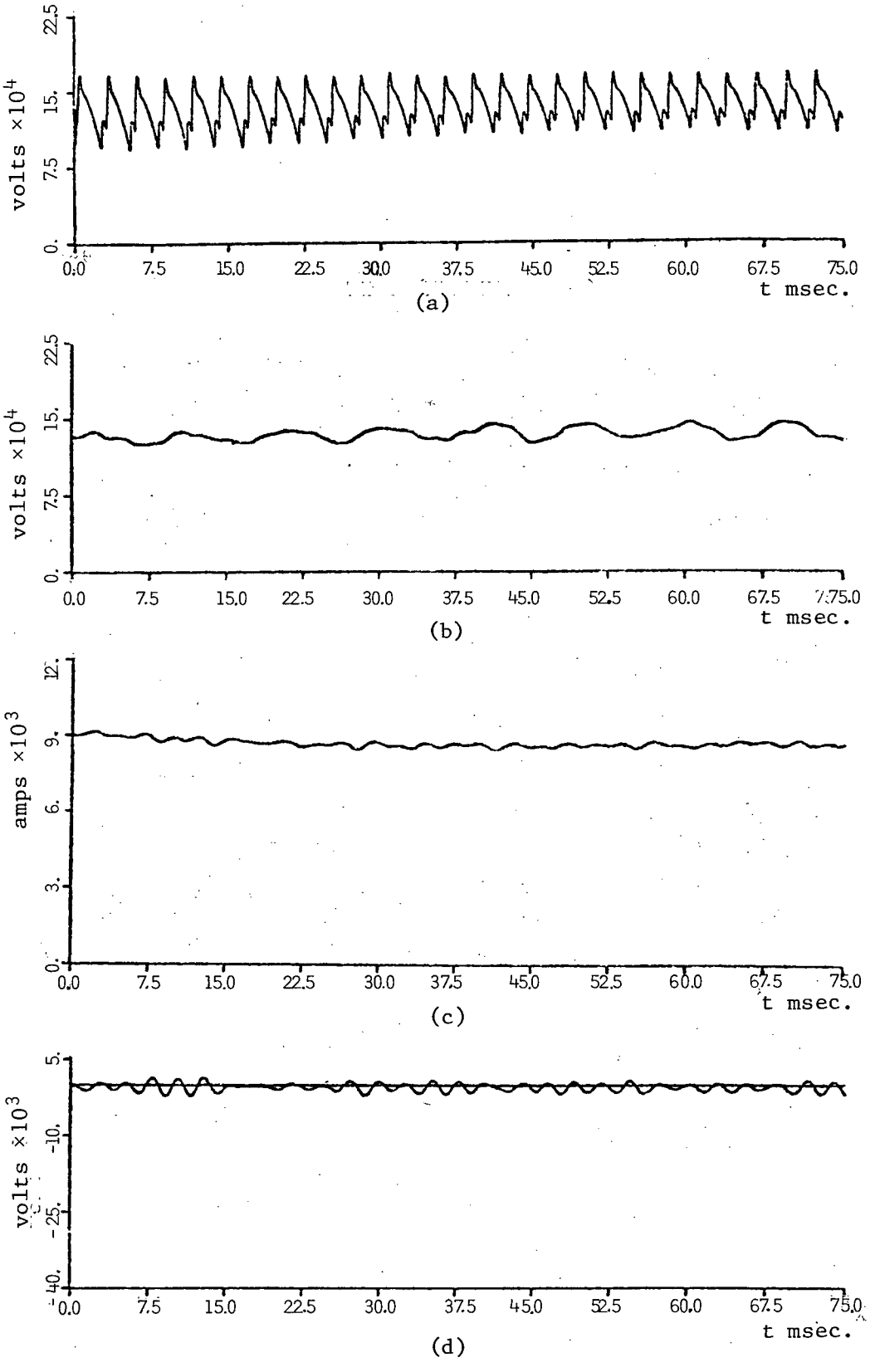
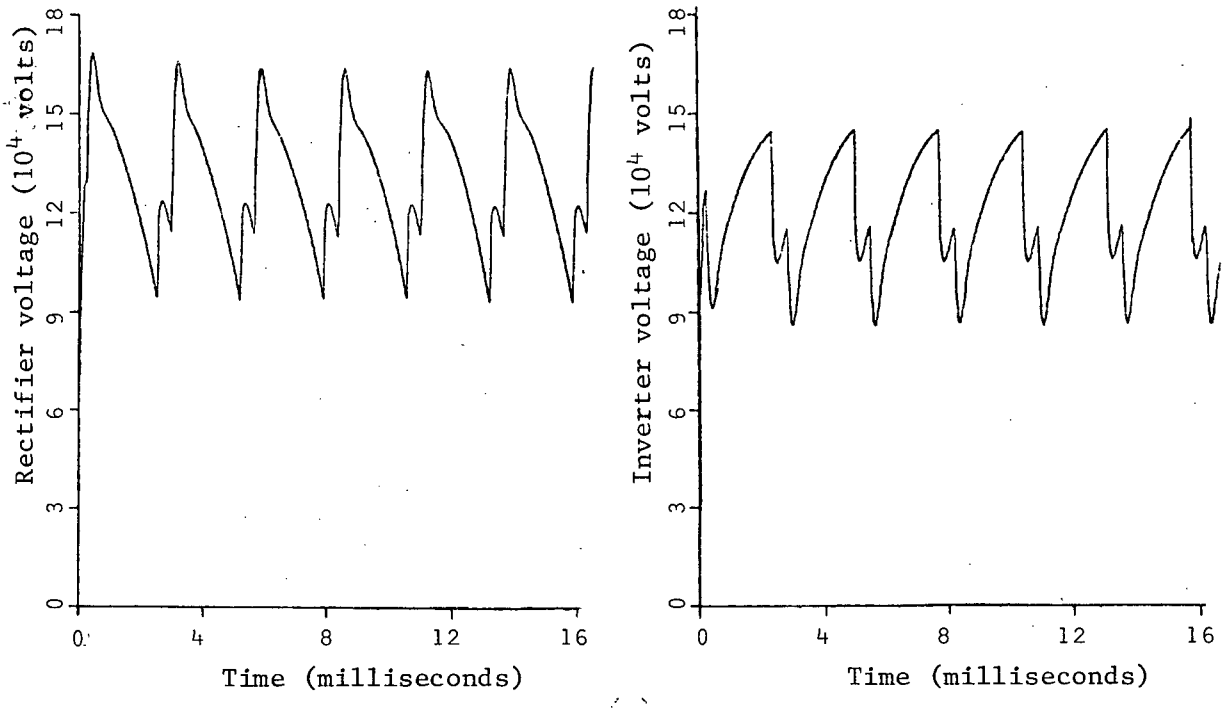
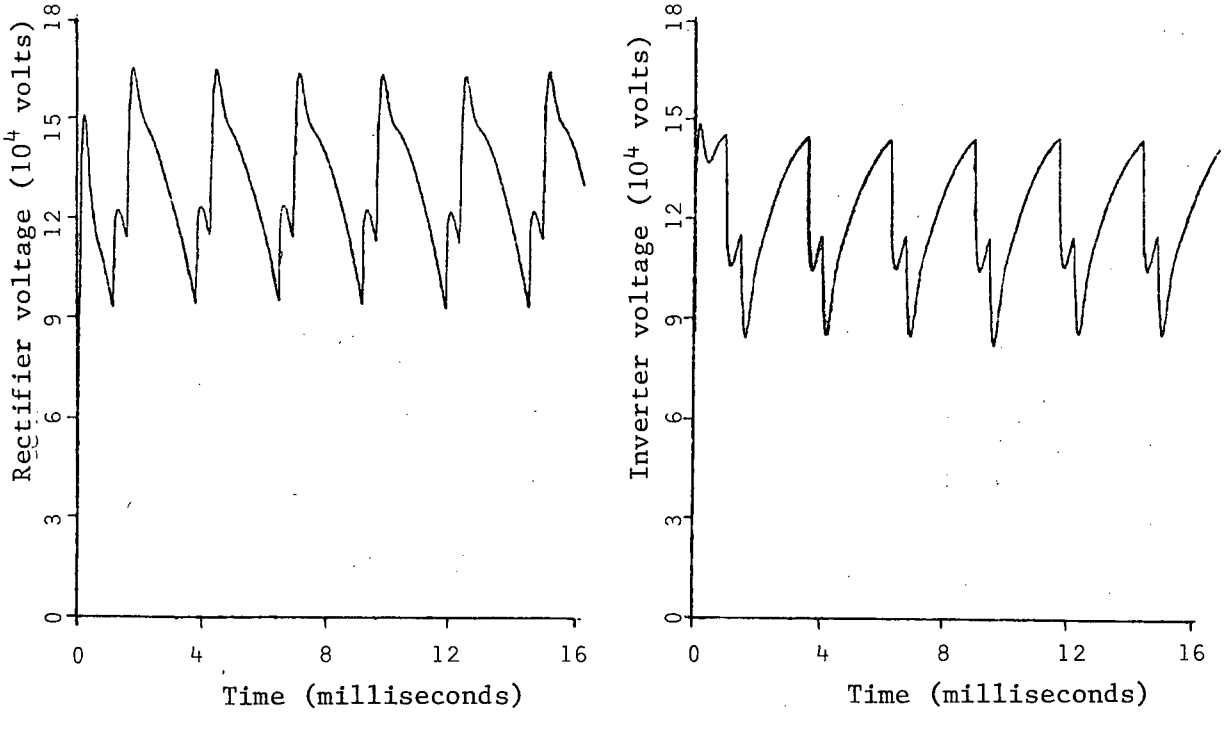


Fig. 3.6 Long run to verify steady state solution: (a) - Rectifier terminal voltage; (b) - DC line voltage; (c) - DC line current; (d) - Electrode line voltage.



(a)



(b)

Fig. 3.7 Simulation with DC starts at (a) a point of commutation; (b) middle of non-commutation interval.

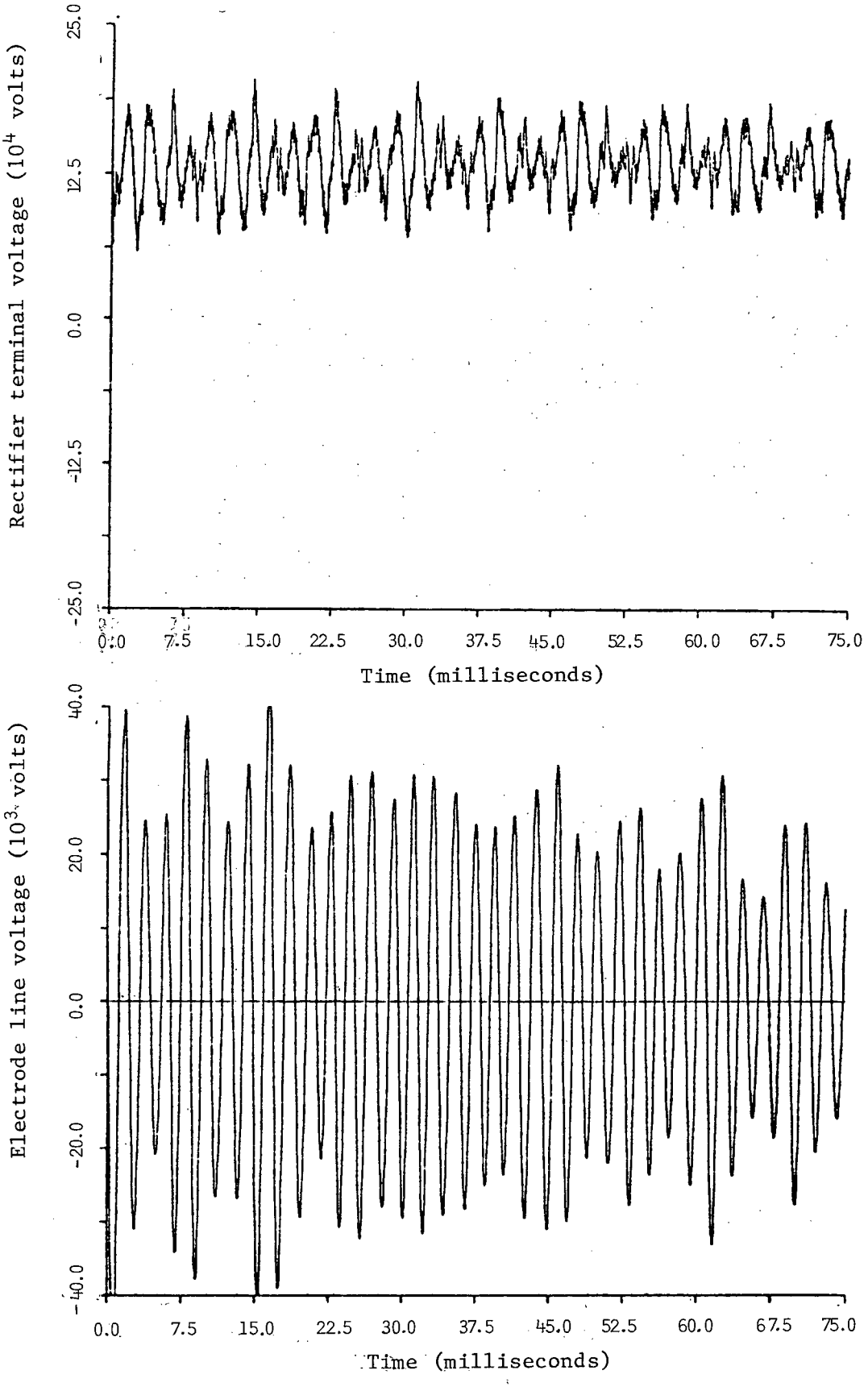


Fig. 3.8 Simulation results with electrode line starts at zero initial conditions.

oscillation on the electrode and an erroneous waveform at the converter terminal. The simulation does not settle to steady-state even after a few cycles. Since most ac/dc system simulations consist of a large number of components, the initialization process described must be done with extraordinary care. It is believed that with some program changes in the steady-state subroutine to handle the superposition of solutions at different network frequencies, the whole initialization process could be done automatically. This is beyond the scope of this thesis, and a possibility for future improvements.

4. HARMONIC ANALYSIS

One advantage of a detail converter model is its ability to simulate the interaction between the ac and dc sides of the network accurately. This is important both in steady-state and transients analysis. One major criterion in HVDC system design is its harmonic performance. The appearance of undesirable harmonics[13,20] may cause overheating of capacitors and generators, interference in telecommunication circuits, shortened life of incandescent lights, instabilities of the converter control, and remote resonances in the ac system. Corrective measures must be imposed to eliminate them at the source or at least to reduce them to permissible levels. A good amount of published literature describes the different methods for determining the level of harmonic generation which can be anticipated from a converter installation. The main objective of this chapter is not to discuss these laborious mathematical procedures in detail, but rather to show the usefulness of the digital time-domain simulation in predicting the harmonic behaviour, and to compare the results with those obtained from the theoretical calculations where appropriate.

4.1 Analyzing Method

A Fourier Analysis Program was used to analyze the simulation results. The output quantities of the Transients Program (node voltages, branch currents, branch voltages, etc., as a function of time) can be stored in a file for further processing. Once the simulation settles into steady-state, the values within one period can be expressed as

$$f(x) = \sum_{i=0}^{\infty} a_i \cos(ix) + \sum_{i=0}^{\infty} b_i \sin(ix) \qquad (4.1)$$

where a_i, b_i are the coefficients of the Fourier series.

The program, originally written by H.W. Dommel[21], reads all the n data points within a user-specified period and computes the cosine coefficients a_o .... a_m and sine coefficients b_o .... b_m of equation (4.1) as well as the magnitude of

$$C_i = \sqrt{a_i^2 + b_i^2} \tag{4.2}$$

with

$i = 0, 1, ... m$

$m = \frac{n}{2}$, when n is even

$m = \frac{n-1}{2}$, when n is odd

The resulting finite series

$$F(x) = \sum_{i=0}^{m} a_i \cos(ix) + \sum_{i=0}^{m} b_i \sin(ix) \tag{4.3}$$

will pass through each data point of the specified period, and provide a smooth interpolation between points with the least number of harmonics. A FORTRAN listing of the program is shown in Appendix 3.

In order to obtain higher order harmonics, the time step for the simulation must be chosen in such a way that the computation cost does not increase unnecessarily on one hand, and that the results are still accurate enough on the other hand. Experience has shown that for analyzing characteristic harmonics, a sampling rate of 10 points per cycle at the highest frequency of interest will give reasonable solutions. In studying imbalance factors, however, a step length of less than one degree of fundamental frequency should be used.

4.2 Harmonic Contents

A converter bridge will produce to some noticeable degree all the lower order harmonics. These harmonic currents appear in both the ac and dc networks, and may penetrate into the power system far from the connection point. Under normal operating conditions, some harmonics are predominant in magnitude. They are usually referred to as normal or characteristic harmonics and attract most of the attention in system design. They are of the following order:

DC side : $h = kp$

AC side : $h = kp \pm 1$

where

h = order of a harmonic

k = pulse number

p = 1, 2, 3 ... any positive integer

Based on the assumptions of perfectly smoothed direct current (i.e. infinite smoothing inductance on the dc side) and symmetrical operation of the ac network, the amplitude of the characteristic ac side current harmonics for overlap angles of less than 60° may be written as [13, 14]:

$$I_h = \frac{I_{10} F_1}{hD} \tag{4.4}$$

where

I_{10} = rms fundamental alternating current with no overlap

D = $\cos \alpha - \cos (\alpha+u)$

U = overlap angle

F_1 = $[A^2 + B^2 - 2AB \cos (2\alpha+u)]^{\frac{1}{2}}$

A = $\dfrac{\sin [(h-1)\, u/2]}{h-1}$

B = $\dfrac{\sin [(h+1)\, u/2]}{h+1}$

and the rms value of the harmonics of the direct voltage is given by

$$V_{dh} = V_{do} F_2 \tag{4.5}$$

where

$$F_2 = [C^2 + D^2 - 2CD \cos (2\alpha+u)]^{\frac{1}{2}}$$

$$C = \frac{\cos [(h-1) u/2]}{h-1}$$

$$D = \frac{\cos [(h+1) u/2]}{h+1}$$

These equations are for idealized conditions, and the true value will vary from the results obtained with them depending on the operating condition of the particular system. In the past, planning engineers computed these ideal harmonic levels and used empirical values based on the contractor's experience of previous HVDC installations to make modifications[22]. As this discussion progresses, the practicality of the simplifying assumptions will be investigated.

The first questionable assumption is the perfect smoothness of direct current. In reality, the smoothing reactors in HVDC installations are typically in the range of 0.5 to 1.0 H. Table 4.1 compares the harmonics contained in the simulated current curve with two theoretical calculations, one based on equation (4.4) and another derived earlier by Brown and Smith[23] who described the current wave shape on the ac side of the mercury arc rectifier under pure resistive load condition as:

$$i = \frac{3.308\ I_d}{\pi} [\sin \theta - 0.226 \sin 5\theta - 0.113 \sin 7\theta$$

$$+ 0.091 \sin 11\theta + 0.065 \sin 13\theta - 0.0567 \sin 17\theta \ldots\ldots] \tag{4.6}$$

The harmonics extracted from the digital simulation lie in between the two extremes. Furthermore, a finite inductance also implies that the current wave shape is affected by the nature of the load. Simulated values of ac

ORDER OF HARMONIC	MAGNITUDE OF HARMONIC CURRENT			
	Calculation based on L=0	EMTP Simulation Results		Calculation based on L=∞
		L = .5H	L = 1H	
1	1.000	1.000	1.000	1.000
5	.226	.202	.198	.192
7	.113	.131	.135	.132
11	.091	.079	.080	.074
13	.065	.065	.067	.057
17	.0567	.0404	.0427	.0354
19	.0454	.0339	.0352	.0273
23	.0412	.0183	.0207	.0153
25	.0349	.0139	.0148	.0108

Table 4.1 Comparison of current harmonics obtained from theoretical calculations and from Fourier analysis of simulated curves.

characteristic harmonic currents as a function of direct current are given in Fig. 4.1. The overlap angle, which results from the commutating reactance, affects the harmonic content as the loading condition changes. This should be taken into account in the optimal design of the filters, the converter transformers and the smoothing reactors.

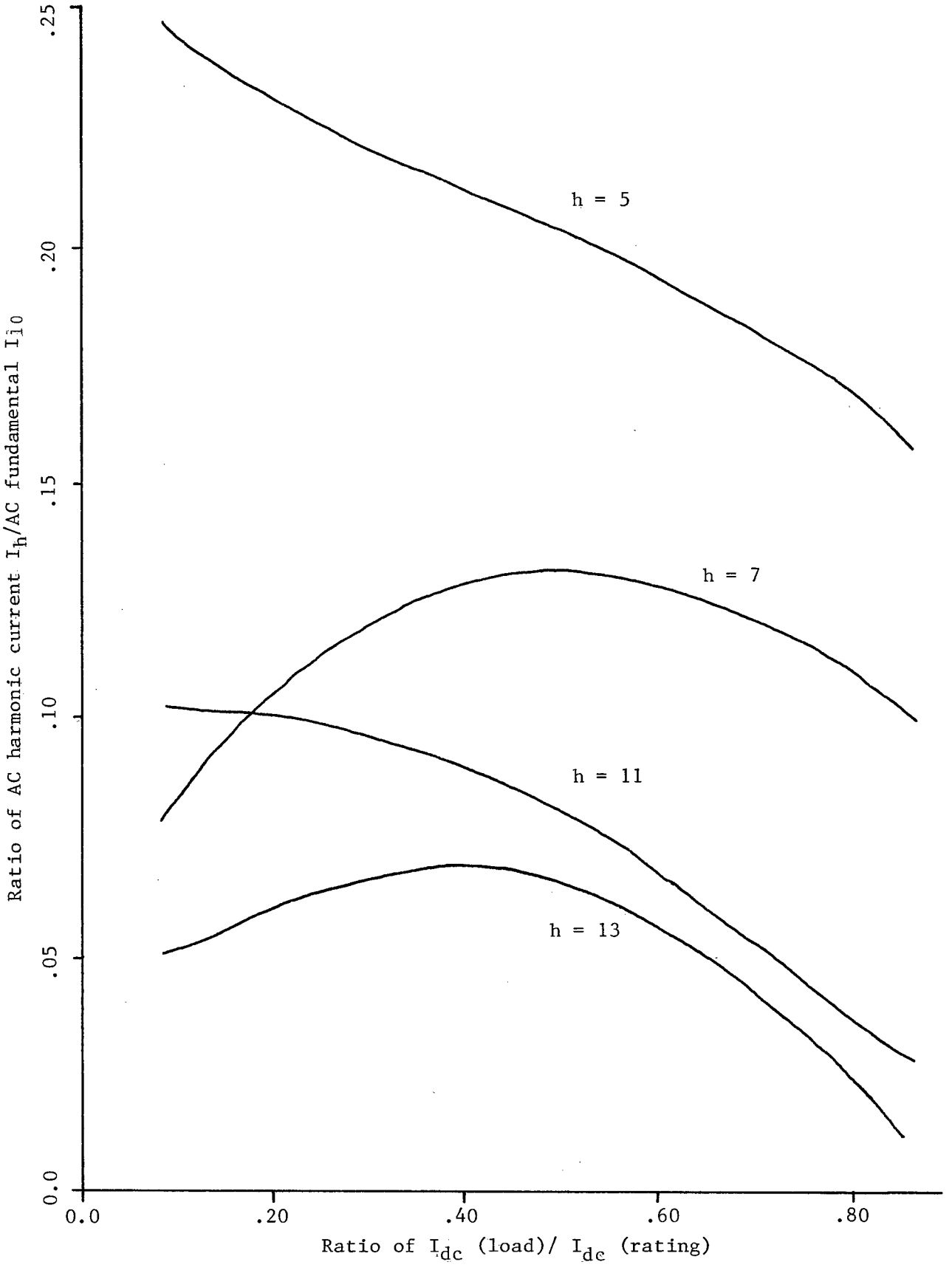


Fig. 4.1 Simulated AC Characteristic Harmonic Current for 6-pulse Operation.

4.3 Abnormal Harmonics

The assumption of ideal balanced (symmetrical) operation is also not realistically achievable. Asymmetrical conditions include[25,26] firing angle errors from converter control, distortions of the ac bus voltage waveforms, imbalances in the ac system voltages and unequal transformer phase impedances. These imperfections result in the generation of non-characteristic or abnormal harmonics. The effect of imbalances in the ac system voltages on the dc harmonics was studied. Table 4.2 contains the magnitude of the harmonic voltages on the dc side due to imbalance in the voltage of one phase of the ac bus. The imbalances in magnitude and phase angle are -5% of the nominal value. Results show that the characteristic harmonics do not change much but an appreciable amount of even harmonics are generated. These agree with the findings of Mathur and Sharaf[24]. In practical systems, a certain degree of different imbalance factors is inevitable. Most imbalances result from an interaction among various phenomena. For example, one or more phases of the ac voltages can be depressed as a result of a remote fault, which will lead to the generation of certain abnormal harmonics. These harmonics will propagate into the ac system, which in turn may lead to voltage distortion. Such cumulative effects cannot be described by simple mathematical formulations. The Transients Program is capable of simulating cases with combinations of imbalance factors. For example, a situation where the supplying ac voltages are at $1.0\underline{/-90^\circ}$, $.98\underline{/151.2^\circ}$, $1.02\underline{/31.2^\circ}$ p.u., has been analyzed. Fig. 4.2 shows that the magnitudes of some non-characteristic harmonics are comparable to those of the characteristic ones in this case.

There is no doubt that this simulation approach for obtaining non-characteristic harmonics offers a relatively easy and economical way to gain a deeper and more systematic understanding of the causes and effects in the

HARMONIC ORDER	RECTIFIER SIDE			INVERTER SIDE		
	Balanced Operation	Imbalance of AC		Balanced Operation	Imbalance of AC	
		Magnitude	Phase		Magnitude	Phase
1	.0000	.0017	.0018	.0009	.0007	.0021
2	.0033	.0208	.0375	.0019	.0172	.0381
3	.0015	.0019	.0020	.0008	.0008	.0005
4	.0007	.0084	.0148	.0008	.0059	.0081
5	.0007	.0015	.0004	.0022	.0022	.0016
6	.1479	.1394	.1463	.1519	.1469	.1522
7	.0025	.0034	.0023	.0046	.0044	.0048
8	.0007	.0104	.0191	.0024	.0115	.0176
9	.0019	.0027	.0014	.0005	.0004	.0001
10	.0010	.0065	.0106	.0004	.0031	.0056
11	.0016	.0034	.0018	.0004	.0004	.0003
12	.0472	.0413	.0446	.0439	.0395	.0440
13	.0017	.0028	.0021	.0004	.0002	.0013
14	.0012	.0072	.0113	.0011	.0052	.0086
15	.0015	.0029	.0009	.0006	.0005	.0003

Table 4.2 Comparison of dc voltage harmonics under balanced operation and imbalance in magnitude and phase in one phase of the ac bus.

generation of harmonics on the ac and dc side of converters. Moreover, current and voltage loadings in each element of the filter arms are readily available, which are valuable to the engineers who must select the protective level of these devices.

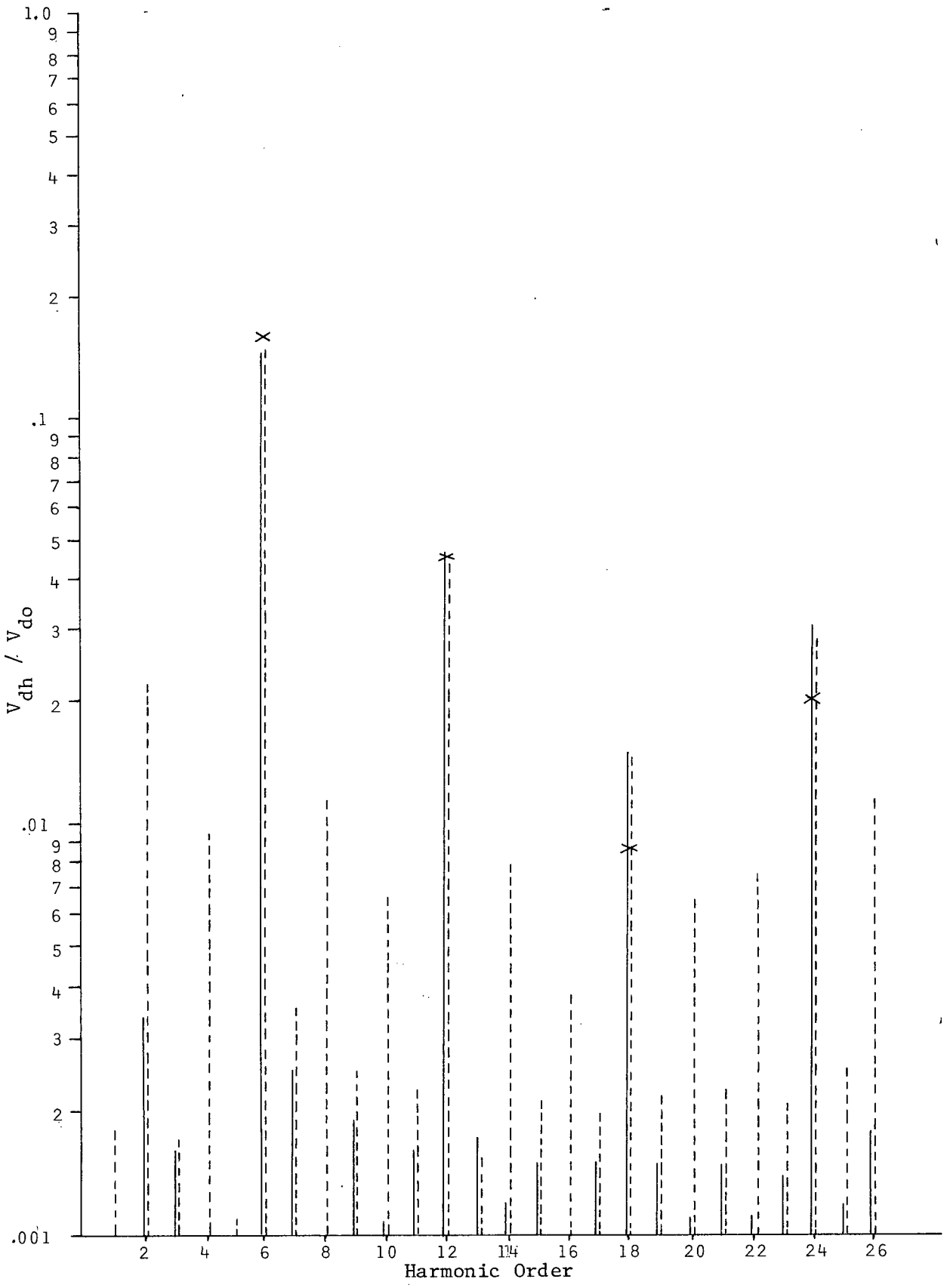


Fig. 4.2 Harmonic voltage on the dc side of the rectifier terminal:
—— balance operation; - - - imbalance operation;
× level of characteristic harmonics calculated by equation (4.5).

5. TRANSIENTS SIMULATION

Two examples are presented in this chapter to test the capability of the converter model in transients simulations. Part of the network from the Pacific HVDC Intertie System is used. The transmission line data and the converter equipment layout of the system is included in Appendix 4.

5.1 Point to Point Operation

As a preliminary test, a simple two terminal case was studied. Results using the simplified model mentioned in Chapter 1 were used as a reference. The simplified model was developed in the early 1970's[27] for studies connected with DC circuit breaker tests. It simulates the HVDC converter station as a dc voltage source whose amplitude is controlled by its current output. With this simplified model, the ac networks and the converter transformers are totally ignored and the valve and anode dampers are represented as an R C-branch in parallel with the dc source. In the detailed case, the system configuration is similar to Fig. 2.1. The ac side behind each converter is represented as ac voltage sources behind Thevenin equivalent impedances, whose values can be found from the positive and zero sequence short-circuit MVA. The converter transformers are connected as wye grounded/wye and the valve and anode dampers are represented in detail. The dc line is 850 miles long and operates in monopolar ground return mode. A line-to-ground fault was applied 50 miles from the rectifier end at time t = 10 msec. The voltage and current at the rectifier terminals are shown in Fig. 5.1 for both types of models (see Appendix 5 for the input listings of both runs). The agreement is reasonably good. The phase shift between the two curves may be due to the exclusion of ac circuits and the lumped

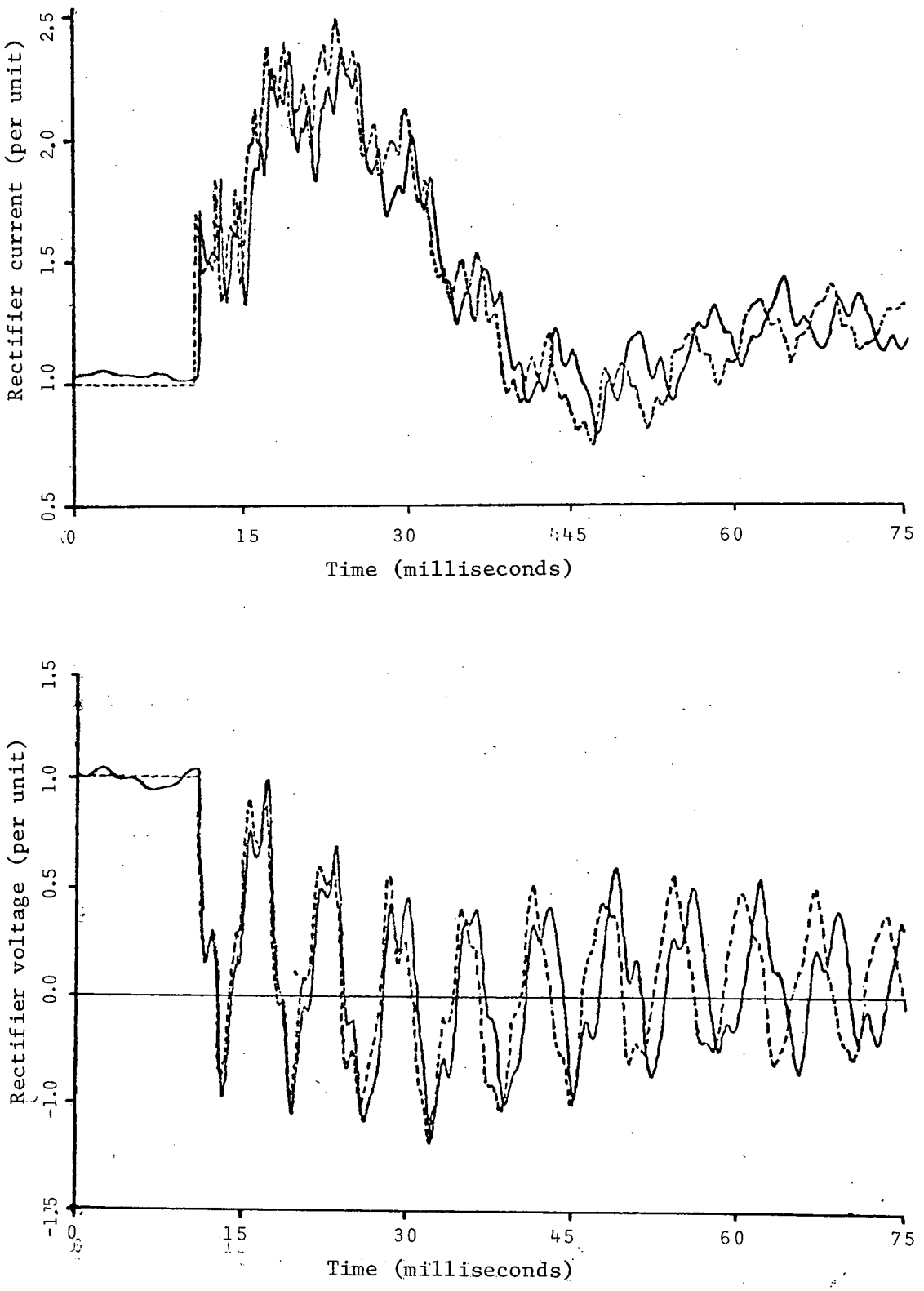


Fig. 5.1 Comparison between simplified and detailed converter station models for a fault on the dc line. Solid line = detailed model; dotted line = simplified model.

representation of dampers in the simplified simulation. In such simple cases, the simplified model does save computation time, while the detailed model provides more insight into the stress on the conversion components and the interaction between the ac and dc sides.

5.2 Three-Terminal Operation

To check the performance of a prototype dc circuit breaker in the field, several tests were conducted on the Pacific HVDC Intertie System[8,15]. The system was tapped as a three-terminal system with constant voltage rectifier control and independent constant current controls on the two inverters. The network set-up is shown in Fig. 5.2, and the system steady-state conditions before the staged fault test are summarized in Table 5.1.

Two manually-initiated faults were applied, a close-in fault by operating an ac breaker which was connected to ground through a 5Ω resistor, and a remote fault by dropping a wire pendulum to short the pole conductor to a tower at 250 miles away from the breaker. Melvold et al.[15] made some comparisons between field tests and computer simulations using the simplified model. The same arrangement was simulated using the detailed model. A sample data deck of the simulation is included in Appendix 6. The resulting curves were superimposed with the results given in reference [15]. As seen in Fig. 5.3 and 5.4, closer agreement with the field test measurements can be obtained using the detailed model. The converters were operated with abnormally large valve voltage stresses resulting from the large commutation margins. Totally ignoring the effects of the ac circuits in the simplified simulation may cause the inaccurate prediction of the current transfer among the terminals. Furthermore, the slight disagreement between the field tests and the detailed simulation, primarily in the form of high frequency oscil-

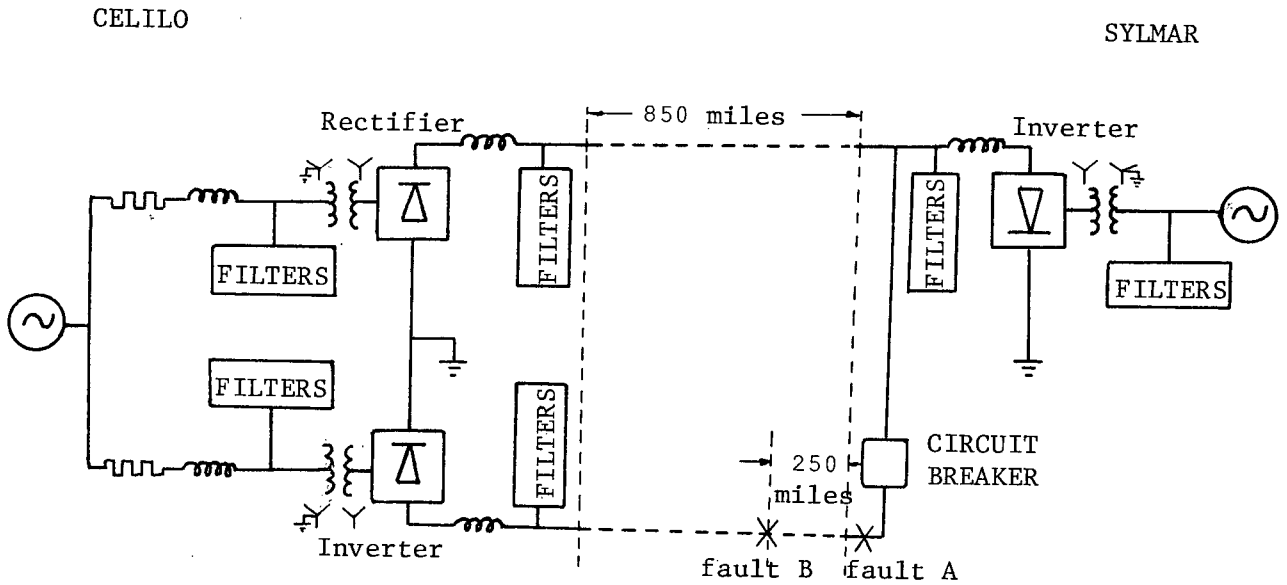


Fig. 5.2 System Configuration for DC Circuit Breaker Test

FAULT	CELILO RECTIFIER	SYLMAR INVERTER	CELILO INVERTER
CLOSE-IN	69.2KV/630A	63KV/330A	53.2KV/350A
REMOTE	70.5KV/558A	60KV/290A	50.5KV/306A

TABLE 5.1 Steady-State System Parameters Before Fault

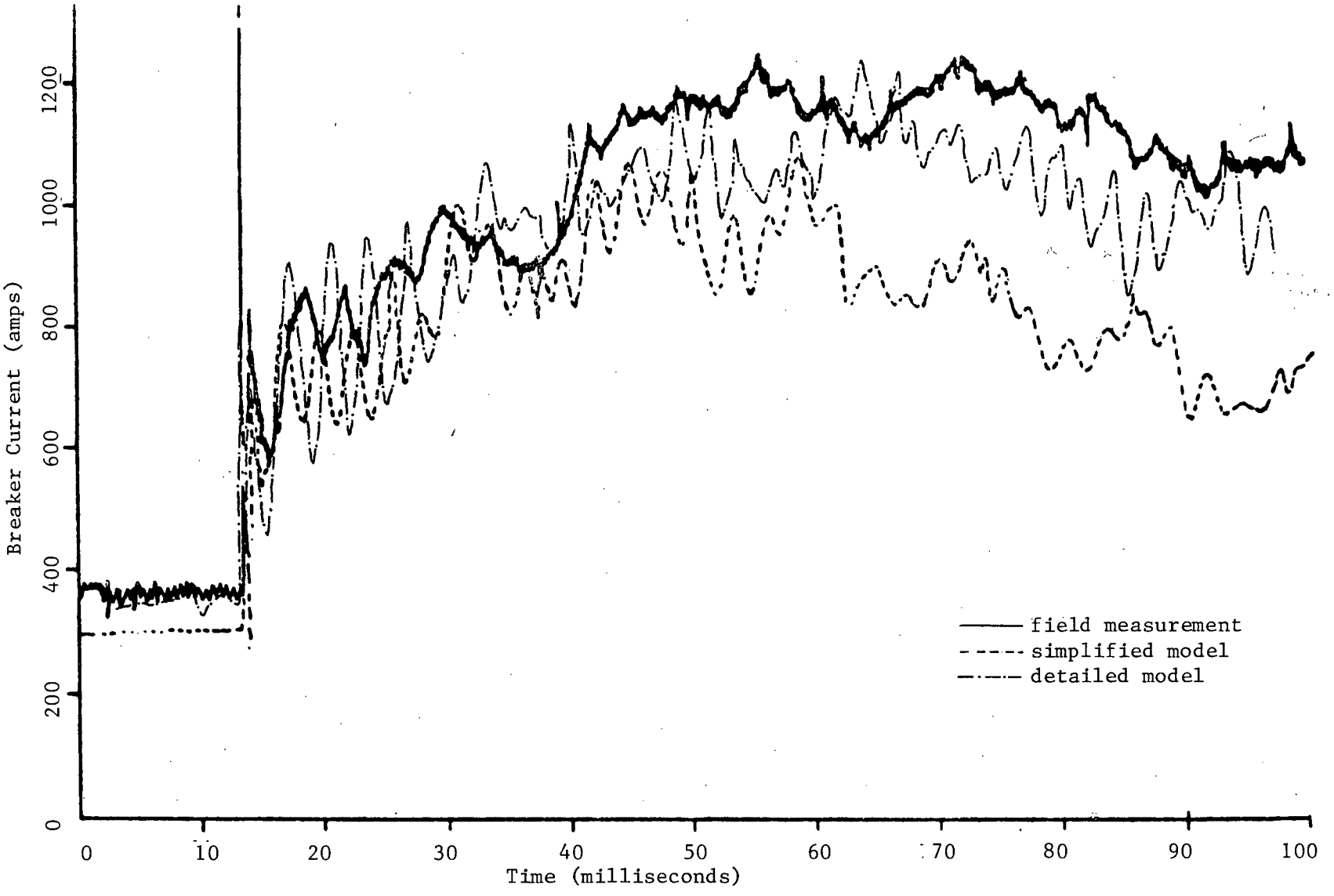


Fig. 5.3 Current through dc breaker following a close-in fault.

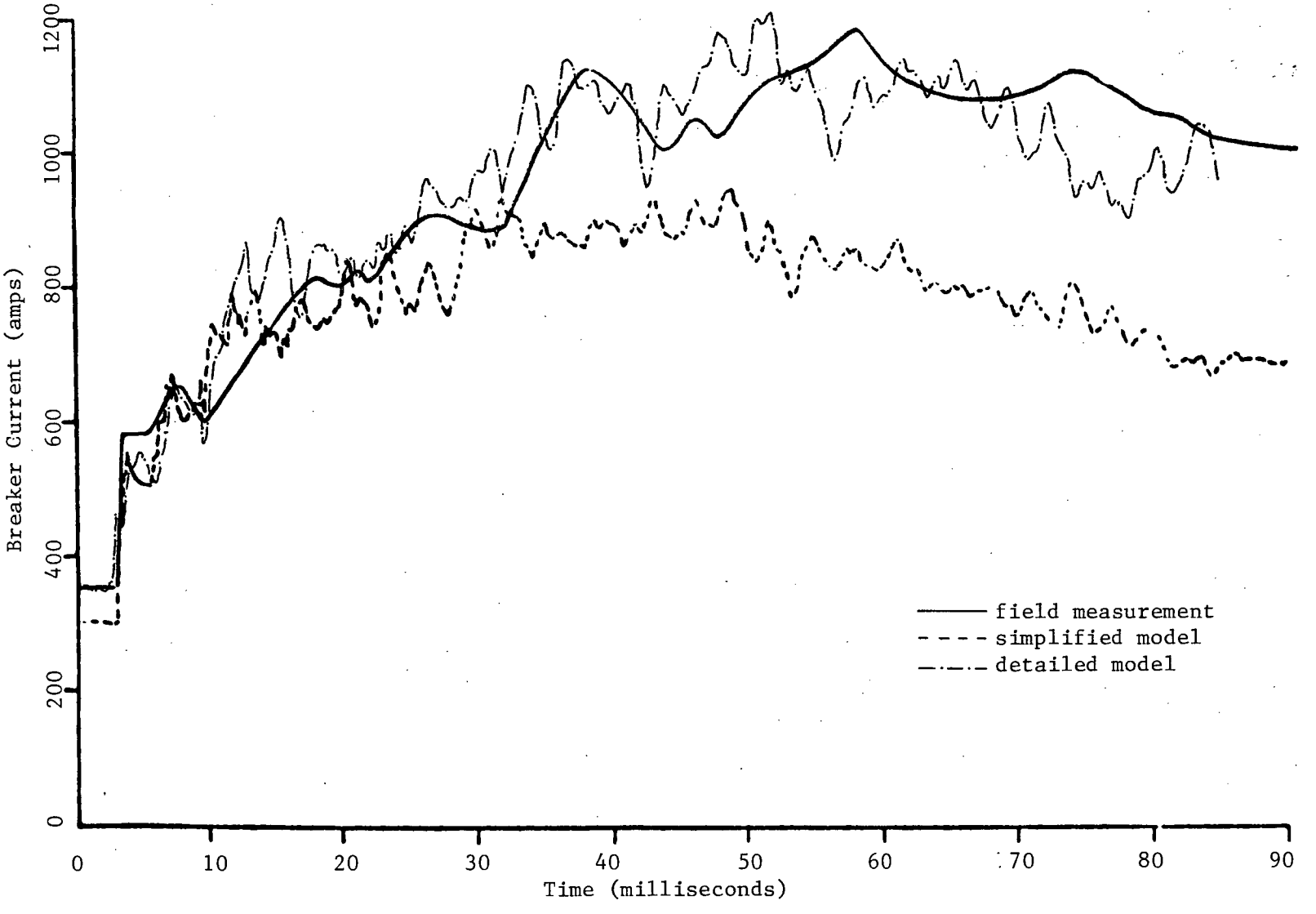


Fig. 5.4 Current through dc breaker following a remote fault.

lations, may be attributed to the inability to represent the frequency dependence of line parameters in the UBC version of the Transients Program.

6. CONCLUSIONS

This thesis describes the development of a new converter model which allows the user to represent HVDC converter valves and their associated firing control systems in the UBC version of the Electromagnetic Transients Program. The modified program can be used to simulate interactions between the ac and dc side and the behaviour of the control system for any type of steady-state or transient operating condition.

The new model takes account of the actual hardware arrangement of the control amplifier which leads to a more accurate representation of the limiters. Efforts have been made to minimize unnecessary computations in the initialization process. The method developed in this thesis is very economical, but it could be improved and made more or less foolproof if the whole procedure were done automatically. This would be a worthwhile topic for future investigations.

The model was applied to harmonic steady-state analysis and transient analysis to verify its capability. In the latter application, simulation results came close to field measurements. However, it should be realized that the frequency-dependent characteristics of line parameters had been neglected in these studies. Considering the complex frequency spectra associated with the harmonics and transients, this would definitely contribute some inaccuracies in the simulation. Modelling of frequency-dependent parameters is the subject of an ongoing Ph.D. project in this Department, and therefore beyond the scope of this M.A.Sc. thesis.

In terms of complexity, capability and flexibility, this model lies in between the simplified dc source model and the 'TACS' package[7]. It

is adequate and particularly useful for basic studies in the research environment of a university. The model is developed not as a substitute to either of the two existing features but as a supplement to these.

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APPENDIX 1

Subroutine VALCON Programme Listings

```
      SUBROUTINE VALCON(ISTEP,DELTAT,KSWTCH,KPOS3)
      COMMON /THYRIS/THYR(51),THYR2(51),DCCUR(10),DCK(10),DCT1(10),
     1 DCT2(10),DCT3(10),DCK1(10),DCK2(10),DCMIN(10),DCMAX(10),
     2 ACVA(10),ACVB(10),ACVC(10),PHSHIF(10),
     3 ACVAI(10),ACVBI(10),ACVCI(10),COMR(10),
     4 DCINI(10),DFREQ(10),ICON(51),IFIRE(51),NGROUP,IMODE(10),
     5 NCOUT(10)
      DIMENSION DELAY(10),COUNT(51),EALFA(10),EMAX(10),CTIME(10),
     1 EMIN(10),X(10),KPOS3(51),NMODE(10),CORDER(10),
     2 CMARG(10),XCUR(10),XB(10)
      DOUBLE PRECISION THYR,THYR2,DCCUR,DELTAT,DELAY,COUNT,DCK,DCK1,
     1 DCK2,DCT1,DCT2,DCT3,DCMIN,DCMAX,DCINI,EALFA,DFREQ,EMAX,EMIN,
     2 DELTA2,T,A,B,P,X,ACVA,ACVB,ACVC,PHSHIF,ACVAI,ACVBI,ACVCI,
     3 CTIME,CORDER,CMARG,COMR,XCUR,XB
C     ***** START CONTROL GROUP LOOP
      DO 104 J=1,NGROUP
      DCCUR(J)=DABS(DCCUR(J))
      IF(ISTEP.GT.0) GO TO 101
C     ***** INITIALIZATION BEFORE ENTERS TIME STEP LOOP
      CORDER(J)=DCCUR(J)
      CTIME(J)=0.D0
      NMODE(J)=1
      I=IMODE(J)
      IF(IABS(I).GT.3)NMODE(J)=2
      IF(I.LT.0)NMODE(J)=-NMODE(J)
      IMODE(J)=IABS(I)-3*(IABS(NMODE(J))-1)
      IF(J.GT.1) GO TO 103
      DO 102 I=1,KSWTCH
      COUNT(I)=0.D0
      IFIRE(I)=0
  102 CONTINUE
  103 DELTA2=DELTAT/2.D0
      DFREQ(J)=1.D0/(6.2831853D0*DFREQ(J))
      T=DCT1(J)+DCT3(J)
      P=DCT1(J)*DCT3(J)
      A=1.D0+T/DELTA2+P/(DELTA2**2)
      B=(1.D0+DCT2(J)/DELTA2)*DCK(J)
      XB(J)=2.D0/B
      DCT1(J)=4.D0*P/A/DELTAT
      P=DCINI(J)
      IF(IMODE(J).EQ.2)DCINI(J)=DCMAX(J)
      IF(IMODE(J).EQ.3)DCINI(J)=DCMIN(J)
      EMAX(J)=(DCMAX(J)-DCK1(J))/DCK2(J)
      EMIN(J)=(DCMIN(J)-DCK1(J))/DCK2(J)
      X(J)=0.D0
      T=DCCUR(J)
      IF(IMODE(J).GT.1)T=P
      CMARG(J)=CORDER(J)-T
      XCUR(J)=CORDER(J)-CMARG(J)-DCCUR(J)
      EALFA(J)=(DCINI(J)-DCK1(J))/DCK2(J)
      DCT2(J)=1.D0-DCK(J)*XB(J)
      IF (IMODE(J).GT.1) XCUR(J)=EALFA(J)/DCK(J)
      DCT3(J)=B/A
      DCMAX(J)=2.D0*DCK(J)/A-DCT3(J)
      DCK(J)=1.D0-2.D0/A
      DCMIN(J)=DCMAX(J)*XCUR(J)+DCK(J)*EALFA(J)
      GO TO 105
C     ***** ON EACH TIME STEP
C     ***** CALCULATE AMPLIFIER OUTPUT & DETERMINE OPERATING REGION
  101 A=EALFA(J)
```

```
      DCCUR(J)=CORDER(J)-DCCUR(J)-CMARG(J)
      IF(IMODE(J).EQ.2.AND.DCCUR(J).GT.0.DO)GO TO 106
      IF(IMODE(J).EQ.3.AND.DCCUR(J).LT.0.DO)GO TO 107
      EALFA(J)=DCT3(J)*DCCUR(J)+DCMIN(J)
      XCUR(J)=DCCUR(J)
      X(J)=(EALFA(J)-A)/DELTA2-X(J)
      IF (EALFA(J).GT.EMAX(J)) GO TO 106
      IF (EALFA(J).LT.EMIN(J)) GO TO 107
      IF(IMODE(J).GT.1)WRITE(6,300)J
  300 FORMAT(' CONVERTER NO. ',I3,' BACK OFF FROM LIMIT')
      IMODE(J)=1
      GO TO 108
C     ***** CONVERTER IN UPPER LIMIT
  106 EALFA(J)=EMAX(J)
      IF(IMODE(J).EQ.1)WRITE(6,301)J
  301 FORMAT(' CONVERTER NO. ',I3,' HITS UPPER LIMIT')
      XCUR(J)=EALFA(J)*XB(J)+DCT2(J)*XCUR(J)
      IMODE(J)=2
      X(J)=0.DO
      GO TO 108
C     ***** CONVERTER IN LOWER LIMIT
  107 EALFA(J)=EMIN(J)
      IF(IMODE(J).EQ.1)WRITE(6,302)J
  302 FORMAT(' CONVERTER NO. ',I3,' HITS LOWER LIMIT')
      XCUR(J)=EALFA(J)*XB(J)+DCT2(J)*XCUR(J)
      IMODE(J)=3
      X(J)=0.DO
  108 DCMIN(J)=DCMAX(J)*XCUR(J)+DCK(J)*EALFA(J)+DCT1(J)*X(J)
  105 IF(IABS(NMODE(J)).EQ.1.OR.ISTEP.EQ.0)GO TO 160
      A=6.2831853DO*DFREQ(J)
      CTIME(J)=CTIME(J)+DELTAT
      A=A-CTIME(J)
      IF(A.GT.DELTA2) GO TO 104
      CTIME(J)=0.DO
C     ***** CALCULATING VALVE DELAY TIME
  160 A=DCK1(J)+DCK2(J)*EALFA(J)
      B=DABS(DCK1(J))
      P=A/B
      DELAY(J)=DFREQ(J)*DARCOS(P)
      IF(NCOUT(J).EQ.0) GO TO 104
C     ***** OUTPUT DELAY ON REQUEST
      WRITE (6,11) J,DELAY(J)
   11 FORMAT(1H ,'CONVERTER NO. ',I3,2X,'DELAY IS',E15.6,' SEC. ')
  104 CONTINUE
C     ***** START VALVE COUNT LOOP
      DO 100 I=1,KSWTCH
      K=IABS(KPOS3(I))
      IF(K.NE.4) GO TO 135
      J=ICON(I)
      IF(J.LE.0)GO TO 100
      J=J/10
      JJ=ICON(I)-J*10
      IFIRE(I)=0
      IF(PHSHIF(J).EQ.0.DO)GO TO 137
C     ***** CALCULATE THE COMMUTATING VOLTAGES
C     ***** CONVERTER TRANSFORMER WYE-DELTA CONNECTED
      GO TO (141,142,143,144,145,146),JJ
  141 A=-1.DO*ACVC(J)
      GO TO 117
  142 A=ACVB(J)
```

```
121           GO TO 117
122       143 A=-1.D0*ACVA(J)
123           GO TO 117
124       144 A=ACVC(J)
125           GO TO 117
126       145 A=-1.D0*ACVB(J)
127           GO TO 117
128       146 A=ACVA(J)
129           GO TO 117
130     C     ***** CONVERTER TRANSFORMER WYE-WYE CONNECTED
131       137 GO TO(111,112,113,114,115,116),JJ
132       111 A=ACVA(J)-ACVC(J)
133           GO TO 117
134       112 A=ACVB(J)-ACVC(J)
135           GO TO 117
136       113 A=ACVB(J)-ACVA(J)
137           GO TO 117
138       114 A=ACVC(J)-ACVA(J)
139           GO TO 117
140       115 A=ACVC(J)-ACVB(J)
141           GO TO 117
142       116 A=ACVA(J)-ACVB(J)
143       117 IF(NMODE(J).LT.0)A=-A
144           IF (ISTEP.GT.0) GO TO 118
145           IF (PHSHIF(J).EQ.0.D0)GO TO 138
146           GO TO (151,152,153,154,155,156),JJ
147       151 P=-1.D0*ACVCI(J)
148           GO TO 120
149       152 P=ACVBI(J)
150           GO TO 120
151       153 P=-1.D0*ACVAI(J)
152           GO TO 120
153       154 P=ACVCI(J)
154           GO TO 120
155       155 P=-1.D0*ACVBI(J)
156           GO TO 120
157       156 P=ACVAI(J)
158           GO TO 120
159       138 GO TO (121,122,123,124,125,126),JJ
160       121 P=ACVAI(J)-ACVCI(J)
161           GO TO 120
162       122 P=ACVBI(J)-ACVCI(J)
163           GO TO 120
164       123 P=ACVBI(J)-ACVAI(J)
165           GO TO 120
166       124 P=ACVCI(J)-ACVAI(J)
167           GO TO 120
168       125 P=ACVCI(J)-ACVBI(J)
169           GO TO 120
170       126 P=ACVAI(J)-ACVBI(J)
171       120 IF(NMODE(J).LT.0)P=-P
172           T=DATAN2(P,A)+1.57079632700
173           IF (T.LT.0.D0) T=T+6.283185307D0
174           IF(NMODE(J).GT.0)GO TO 132
175           IF (T.GT.4.276056675D0) GO TO 100
176           GO TO 131
177       132 IF(T.GT.3.441592654D0)GO TO 100
178       131 COUNT(I)=T*DFREQ(J)
179           GO TO 119
180     C     ***** GENERATION OF FIRING PULSES
```

```
181         118  IF (A.LE.0.D0) GO TO 133
182              COUNT(I)=COUNT(I)+DELTAT
183         119 T=DELAY(J)-COUNT(I)
184              IF (T.GE.DELTA2) GO TO 100
185              IFIRE(I)=1
186         133 COUNT(I)=0.D0
187              GO TO 100
188         135 IFIRE(I)=0
189         100 CONTINUE
190              RETURN
191              END
```

APPENDIX 2

Modifications in the Transients Program

To incorporate the converter model into the U.B.C. Electromagnetic Transients Program, modifications have to be made in the program so that information may be transferred between the main program and the subroutine. The required changes are shown in the FORTRAN 4 listings of Table A2-1.

Explanation of Changes.

File line no.	Comments
53-59.2, 97.2-98	New variables for collecting information required by VALCON.
393-395, 450-451	Reset variables.
399-429, 571	Input control parameters.
1296.06-1296.9	Store node voltages for commutation voltage calculation before entering the time step loop.
1680.2-1681	Call subroutine VALCON.
1687-1687.2	Calculate group number.
1723, 1795	Store valve voltage and current.
1726-1728	Determine the ignition of valves.
1764.2, 1795.2	Avoid premature blocking after the valve fired which cause small current oscillation.
1796	Store dc line current.
1776.2	To make the switch open exactly at time t=0.
1767, 1823	Reset valve voltage and current.
1820	Reset dc line current.
2053.05-2053.6	Store node voltages for commutation voltage calculation at each time step.

TABLE A2.1

Changes in the Transients Program for data transferred to subroutine VALCON

C=Change I=Insertion

```
      DIMENSION KMS(650),YS(650)
      COMMON/HERMAN/          VOLTI(50),VOLTK(50),VOLT(50),VIM(50)
C     DIMENSION ADELAY(51),XMAX(50),XOUT(100),POLAR(51),JJJ(380)
C  FOLLOWING DIMENSION STATEMENT PERTAINS TO VALVE CONTROL PARAMETERS
      COMMON /THYRIS/THYR(51),THYR2(51),DCCUR(10),DCK(10),DCT1(10),
     1 DCT2(10),DCT3(10),DCK1(10),DCK2(10),DCMIN(10),DCMAX(10),
     2 ACVA(10),ACVB(10),ACVC(10),PHSHIF(10),
I    3 ACVAI(10),ACVBI(10),ACVCI(10),COMR(10),
     4 DCINI(10),DFREQ(10),ICON(51),IFIRE(51),NGROUP,IMODE(10),
     5 NCOUT(10)
      DOUBLE PRECISION THYR,THYR2,DCCUR,DCK,DCT1,DCT2,DCT3,DCK1,DCK2,
     1 DCMIN,DCMAX,DCINI,DFREQ,ACVA,ACVB,ACVC,PHSHIF,
     2 ACVAI,ACVBI,ACVCI,COMR
      DOUBLE PRECISION COPT,C,R,CK,CREST,BUS,XOPT,TR,TIME,TSTART,TCLOSE,
.....
C  HISTORY OF DISTRIBUTED LINES IS CHANGED
      LPAST=1250
I  C  CHANGE FOLLOWING STATEMENT IF DIMENSION OF CONTROL GROUP IS CHANGED
      LGROUP=10
.....
      KSWTCH=0
      KCONST=0
      N4=0
      NGROUP=0
I     DO 229 I=1,LBUS
  229 JJJ(I)=0
  209 KSWTCH=KSWTCH+1
      READ(5,77)IT2
   77 FORMAT(I2)
      IF(IT2.NE.16)GO TO 199
      IPRINT=16
      IF(NGROUP.GT.LGROUP)GO TO 9000
      NGROUP=NGROUP+1
      KSWTCH=KSWTCH-1
      BACKSPACE 5
      READ(5,89) N2,IMODE(NGROUP),DCK(NGROUP),DCINI(NGROUP),
     1 DCT1(NGROUP),DCT2(NGROUP),DCT3(NGROUP),DCCUR(NGROUP)
   89 FORMAT(I2,6X,I2,6E10.6)
I     WRITE(6,179) N2,IMODE(NGROUP),DCK(NGROUP),DCINI(NGROUP),
     1 DCT1(NGROUP),DCT2(NGROUP),DCT3(NGROUP),DCCUR(NGROUP)
  179 FORMAT(' CONTROL PARAMETERS: '/1X,I2,10X,I4,6E14.6)
      READ(5,159)DCK1(NGROUP),DCK2(NGROUP),DCMIN(NGROUP),DCMAX(NGROUP),
     1    DFREQ(NGROUP),NCOUT(NGROUP)
  159  FORMAT(10X,5E10.6,19X,I1)
      WRITE(6,149)DCK1(NGROUP),DCK2(NGROUP),DCMIN(NGROUP),DCMAX(NGROUP)
     1    DFREQ(NGROUP)
  149 FORMAT(1H ,16X,5E14.6)
       READ(5,139)(VOLT(K),K=1,3),PHSHIF(NGROUP),COMR(NGROUP)
  139 FORMAT(2X,3A6,2E10.6)
      WRITE(6,129)(VOLT(K),K=1,3),PHSHIF(NGROUP),COMR(NGROUP)
  129 FORMAT(10X,3(A6,2X),2E14.6)
```

TABLE A2.1 (cont'd)

```
      DO 239 J=1,3
      A=VOLT(J)
      DO 249 I=2,NTOT
      IF(A.EQ.BUS(I))GO TO 259
  249 CONTINUE
      WRITE(6,1042) A
      GO TO 239
  259 JJJ(I)=NGROUP*10+J
  239 CONTINUE
      GO TO 209
  199 BACKSPACE 5
      READ(5,35)IT2,BUS1,BUS2,BUS3,BUS4,CK1,A,JJ,J
   35 FORMAT(I2,2A6,4E10.6,23X,I2,I1)

  212 ISOURC(KSWTCH)=0
      ENERGY(KSWTCH)=0.0D0
      THYR(KSWTCH)=0.D0
      THYR2(KSWTCH)=0.D0
      IF(J.LT.2) GO TO 224

      CRIT(KSWTCH)=CK1
      ICON(KSWTCH)=JJ
      GO TO 209
  213 DO 214 I=2,NTOT

C                                          BEGIN OF LOOP FOR ADMITTANCE M
  590 L=1
      DO 3711 I=2,NTOT
      JJ=JJJ(I)
      IF(JJ.LE.0) GO TO 3711
      NJ=JJ/10
      JJ=JJ-NJ*10
      GO TO(3712,3713,3714),JJ
 3712 ACVA(NJ)=E(I)
      ACVAI(NJ)=F(I)
      GO TO 3711
 3713 ACVB(NJ)=E(I)
      ACVBI(NJ)=F(I)
      GO TO 3711
 3714 ACVC(NJ)=E(I)
      ACVCI(NJ)=F(I)
 3711 CONTINUE
      II=0
```

TABLE A2.1 (cont'd)

```
 1678      C                                                    BEGIN OF TIME-STEPS
 1679       1000 KCOUNT=NV
 1680            IF(KSWTCH.EQ.0) GO TO 1009
I1680.2          IF (NGROUP.LE.0) GO TO 3722
 1681            CALL VALCON(ISTEP,DELTAT,KSWTCH,KPOS3)
 1682      C                                          CHECKING SWITCH-POSITIONS FOR CHANGE
 1683       3722 DO 1003 K=1,KSWTCH
 1684            II=KPOS3(K)
 1685            IT1=KPOS1(K)
 1686            ICHECK=KPOS2(K)
I1687             JJ=ICON(K)
I1687.2         IF(JJ.GT.0)JJ=JJ/10
 1688            I=IABS(II)
      :
      :
      :
 1721       2103 CK1=E(N2)-E(N1)
I1722            A=(CK1+ENERGY(K))*0.5D0*POLAR(K)
 1723            THYR2(K)=CK1*POLAR(K)
 1724            ENERGY(K)=CK1
I1726            IF(JJ.LE.0)GO TO 2122
I1727            IF(IFIRE(K).LE.0)GO TO 1002
 1727.2          IF(ISTEP.EQ.0) GO TO 2123
C1727.4    2122 IF(A.LE.0.D0) GO TO 1002
 1728       2123 I=3
 1729            GO TO 2105
      :
      :
      :
 1763       2102 I=1
 1764       2105 TCLOSE(K)=0.D0
I1764.2          IF(I.EQ.3)ADELAY(K)=T+TOPEN(K)
 1765            IF(TCL.GE.0.D0) TCL=T
 1766            KONTRL=4
I1767            THYR2(K)=0.D0
 1768            WRITE(6,2107) TCL
      :
      :
      :
 1773       2108 IF(T.LT.TCL       ) GO TO 1002
 1774            I=2
I1775            IF(JJ.GT.0) GO TO 2105
 1776            IF(II.GT.0 .AND.  TOPEN(K).GT.TMAX) I=0
I1776.2          IF(TCL.LT.0.D0.AND.TOPEN(K).LT.DELTA2)GO TO 2110
 1777            GO TO 2105
 1778       2110 L=N2
      :
      :
      :
 1794            IF(I.EQ.3) BUS1=-A*POLAR(K)
 1795            THYR(K)=BUS1
I1795.2           IF (I.EQ.3.AND.ADELAY(K).GT.T)BUS1=1.D0
 1796            IF(I.EQ.2.AND.JJ.GT.0) DCCUR(JJ)=-A*POLAR(K)
 1797            IF(ISSS.LE.0) GO TO 2112
```

TABLE A2.1 (cont'd)

```
 1818       2118 TCLOSE(K)=0.DO
 1819            IF(I.EQ.3) I=5
I1820            IF(I.EQ.5.AND.JJ.GT.0) DCCUR(JJ)=0.DO
 1821            ENERGY(K)=0.DO
 1822            KONTRL=3
I1823            THYR(K)=0.DO
 1824            WRITE(6,2114) T
 2052       1200 K=K+IT2
 2053            IF(K.LE.IBR) GO TO 1100
 2053.05         DO 1601 I=2,NTOT
 2053.1          JJ=JJJ(I)
 2053.15         IF(JJ.LE.0)GO TO 1601
 2053.2          NJ=JJ/10
 2053.25         JJ=JJ-NJ*10
I2053.3          GO TO (1602,1603,1604),JJ
 2053.35    1602 ACVA(NJ)=E(I)
 2053.4          GO TO 1601
 2053.45    1603 ACVB(NJ)=E(I)
 2053.5          GO TO 1601
 2053.55    1604 ACVC(NJ)=E(I)
 2053.6     1601 CONTINUE
 2054            IF(NV.EQ.0) GO TO 1202
```

APPENDIX 3

Fourier Analysis Programme Listings

```
C FOURIER ANALYSIS PROGRAM FOR DISCRETE POINTS READ IN FROM DEVICE 4
      DOUBLE PRECISION CTIME,GK2,X,TSTART,C1,GK1,S1,GK,AN,CP,AP,S,
     1  BP,A,B,F,BUS,PAIR
      DIMENSION A(1001),B(1001),F(5000),TEXT(17),Y(100),BUS(100),
     1  PAIR(200)
    1 READ(5,2)CTIME,TSTART,IOPT,MLIM,INUMB
    2 FORMAT(2F10.5,I2,2I3)
      IF(INUMB.LT.1)STOP
      REWIND 4
      READ(4)TEXT
      READ(4)NT,DELTAT,IMAX,(BUS(I),I=1,NT)
      READ(4)L,NV,NI,(PAIR(I),I=1,L)
      NT=0
   51 NT=NT+1
      IF(NT.GT.5000) GO TO 56
      READ(4)K,KONTRL,ISTEP,(Y(I),I=1,K)
      F(NT)=Y(INUMB)
      IF(KONTRL.EQ.1) GO TO 50
      GO TO 51
   50 NSTART=TSTART/DELTAT
      IF((TSTART/DELTAT-NSTART).GT.0.5) NSTART=NSTART+1
      N=CTIME/DELTAT
      IF((CTIME/DELTAT-N).GT.0.5)N=N+1
      MM=NSTART+N
      BEGINT=NSTART*DELTAT
      REALCY=N*DELTAT
      K=1
      NPLUS=NSTART+1
      DO 52 I=NPLUS,MM
      F(K)=F(I)
   52 K=K+1
      WRITE(6,5)INUMB,(TEXT(I),I=1,17),N,(F(K),K=1,N)
    5 FORMAT(35H1FOURIER ANALYSIS FOR OUTPUT NUMBER ,I5,' OF ',17A4,/23H
     1ORECORD OF ORDINATES IN,I4,19H EQUIDISTANT POINTS  /(1H ,6F18.7))
      WRITE(6,61)REALCY,BEGINT
   61 FORMAT(//'CYCLE TIME=',F15.10,'SECOND','   ANALYSIS
     1 STARTS AT ',F15.10,'SECOND')
      AN=N
      AN=AN/2.0
      J=AN+1.6
      M=AN+1.0
      IF(MLIM.LT.1) GO TO 62
      IF(MLIM.LT.M)IOPT=0
      IF(MLIM.LT.M)M=MLIM
   62 C1=DCOS(3.141593/AN)
      S1=DSIN(3.141593/AN)
      CP=1.0
      SP=0.
      L=0
   10 L=L+1
      IF(L.GT.M) GO TO 100
      GK2=0.
      GK1=0.
      K=N
   20 GK=F(K)+CP*GK1*2.0-GK2
      GK2=GK1
      GK1=GK
      K=K-1
      IF(K.GT.1) GO TO 20
      AP=(F(1)+GK1*CP-GK2)/AN
```

```
      BP=SP*GK1/AN
      IF(L.EQ.1) GO TO 30
      IF(L.NE.J) GO TO 40
      BP=0.
   30 AP=AP/2.
   40 A(L)=AP
      B(L)=BP
      AP=C1*CP-S1*SP
      SP=C1*SP+S1*CP
      CP=AP
      GO TO 10
  100 WRITE(6,101)
  101 FORMAT(21HOFOURIER COEFFICIENTS/78H HARMONIC     COS-COEFF.      SI
     1N-COEFF.      MAGNITUDE  MULTIPLE OF FUNDAMENTAL)
      CP=1.0/DSQRT(A(2)**2+B(2)**2)
      DO 110 K=1,M
      L=K-1
      AP=DSQRT(A(K)**2+B(K)**2)
      BP=AP*CP
  110 WRITE(6,111) L,A(K),B(K),AP,BP
  111 FORMAT(1H ,I5,2X,4F15.6)
      IF(IOPT.LE.0) GO TO 1
      AN=N
      AN=6.283186/AN
      DO 210 K=1,N
      AP=K-1
      AP=AP*AN
      X=AP
      SP=A(1)
      DO 200 L=2,M
      SP=SP+A(L)*DCOS(X)+B(L)*DSIN(X)
  200 X=X+AP
  210 F(K)=SP
      WRITE(6,211)(F(K),K=1,N)
  211 FORMAT(47HOORDINATES RECOMPUTED WITH FOURIER COEFFICIENTS/(1H ,
     1 6F18.7))
      GO TO 1
   56 WRITE(6,57)
   57 FORMAT('COMPUTED POINTS ARE MORE THAN 5000, INCREASE THE DIMENSION
     1 OF VARIABLE F AS PER NEED')
      STOP
      END
```

APPENDIX 4

Line Parameters and Converter Station Parameters of the Pacific HVDC Intertie

The Pacific HVDC Intertie, which was commissioned on May 21, 1970, was the first overhead HVDC transmission system installed in North America. Fig. A4.1 shows the main circuit of the intertie. The northern section, including the Celilo Converter Station, is owned and operated by the Bonneville Power Administration (BPA), while the southern section and the Sylmar Converter Station is partly owned but operated by the Los Angeles Department of Water and Power (LADWP).

The Intertie is a bipolar (earth return) system with DC rated voltage of ± 400 KV and transmission power capacity of 1440 MW. The dc transmission line is 847 miles long and its line data is shown in Table A4-1.

The rated direct voltage of the dc line is obtained by using six series connected, six-pulse, three phase bridge groups, each rated 133 KV, 1800A. The equipment layouts of the Celilo and Sylmar Converter Stations are basically the same. The bridge circuit and the filter arrangement at Celilo are shown in Fig. A4-2 and Fig. A4-3, respectively.

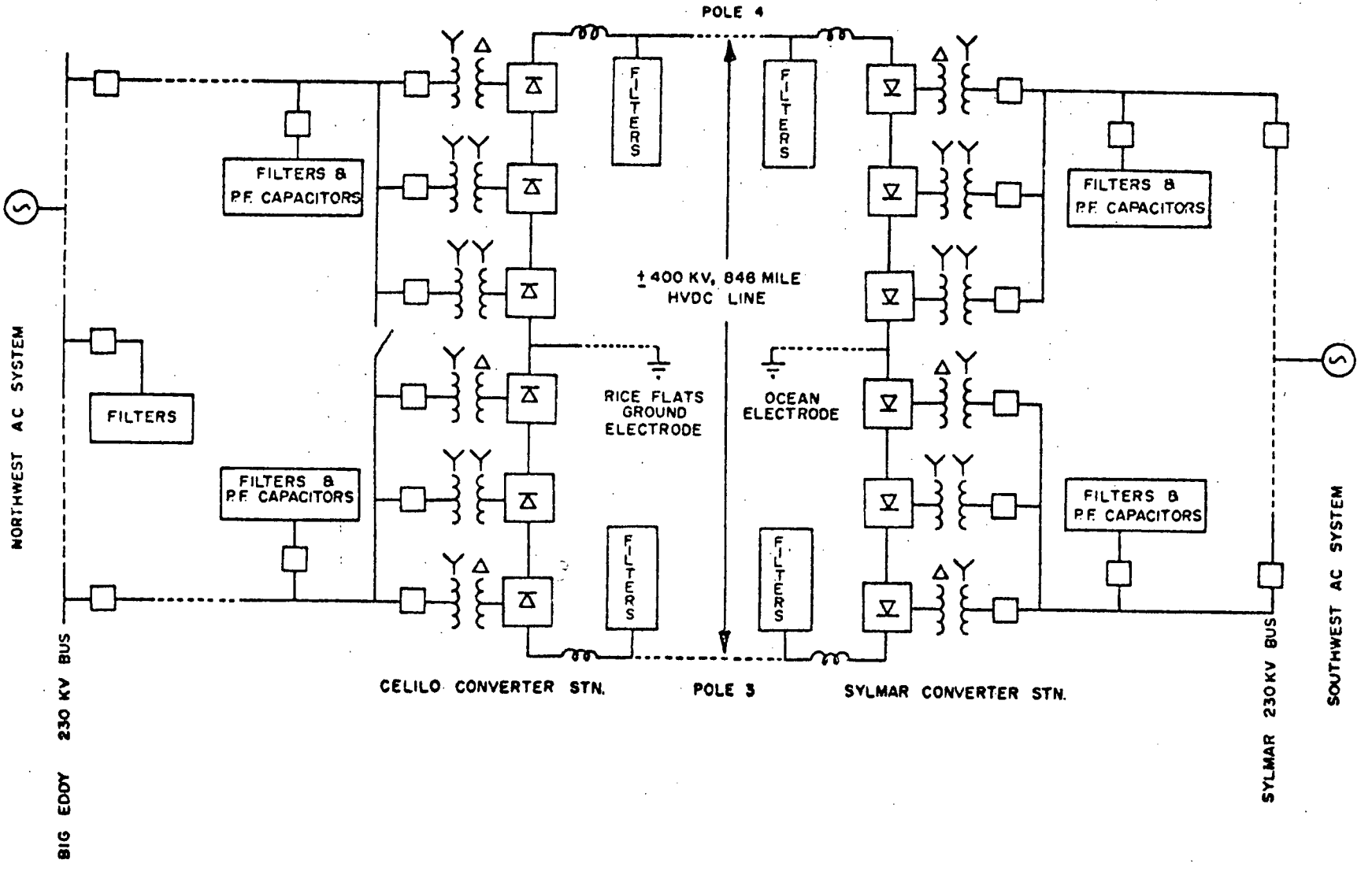

Fig. A4.1 MAIN CIRCUIT OF PACIFIC HVDC INTERTIE

PARAMETERS	MAIN LINE	GROUND WIRE
Number of subconductors	2	1
Subconductor diameter	4.577 cm	1.110 cm
Cross-sectional area of subconductor	1171 mm^2 (2312 MCM)	96.8 mm^2
Bundle spacing	45.7 cm	
Nickname and composition of subconductor	Thrasher ACSR 76/19	ENS
Number of conductors	2 (pos. and neg.)	2
DC Resistance at 25°C	0.0125Ω/km/pole	
Total resistance at 1800 A	19.3Ω/pole	
Average max. height of conductors	24.84 m	33.83 m
Sag	11.55 m	11.55 m
Average height of conductors	18.45 m	26.13 m
Conductor spacing	12.19 m	5.49 m

TABLE A4.1 Transmission line data of the Pacific HVDC Intertie

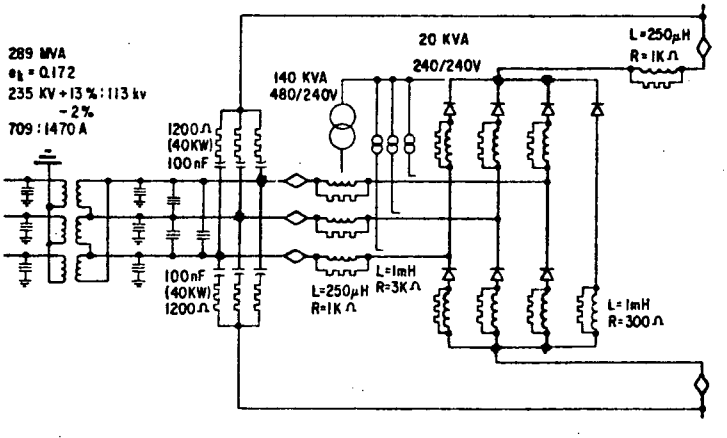

Fig. A4.2 Converter Bridge at Celilo

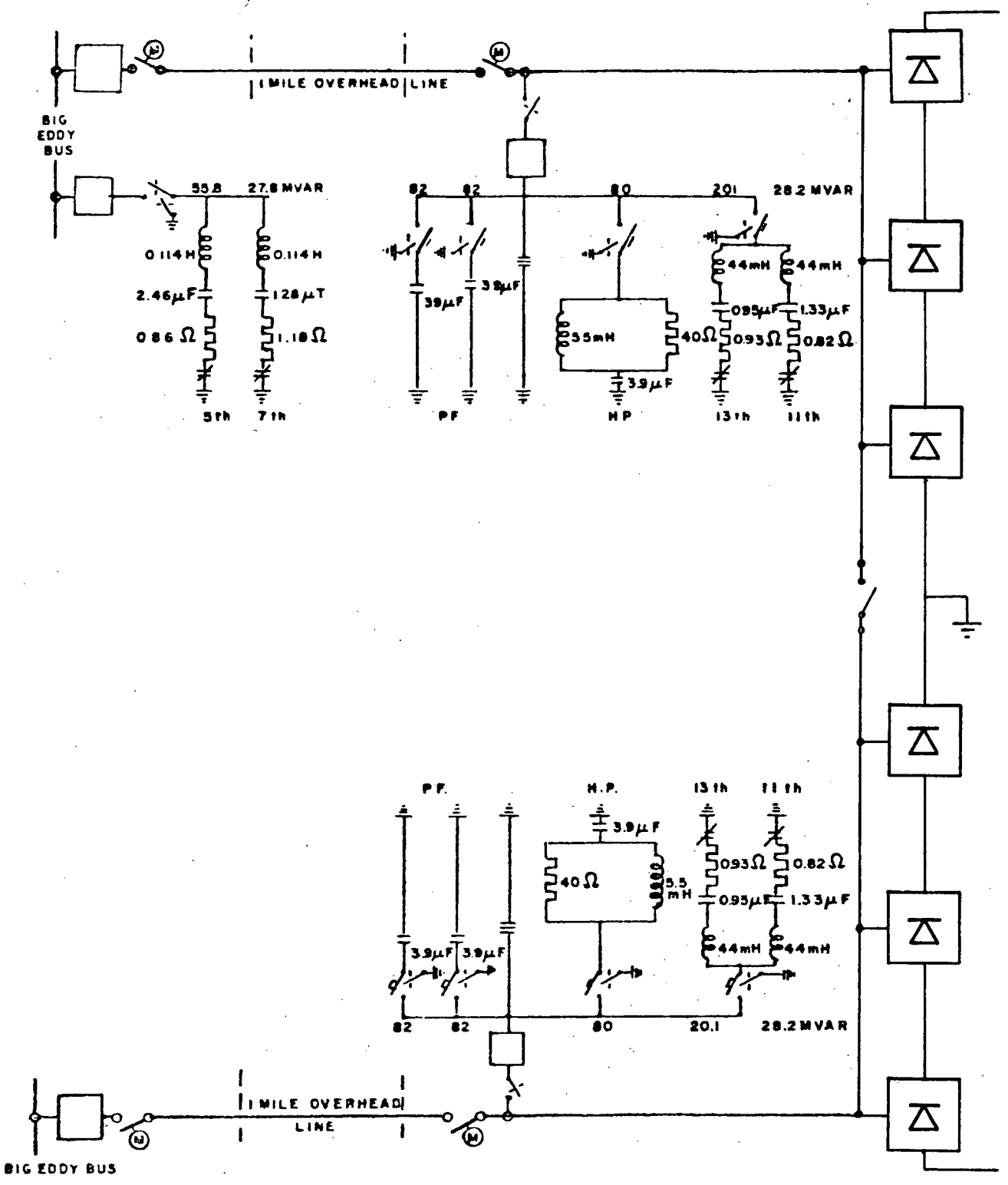

Fig. A4.3 FILTER ARRANGEMENT AT CELILO

APPENDIX 5

Input Listings of the Point to Point Operation Simulation

(a) Simplified Model

```
1     CURRENT CONTROL SOURCE SIMULATION
2          50.E-6     75.E-3  2       1
3        VR     VRT                          500.
4        VRT    CELEC              6.3       280.   .7
5        VR     CELEC              900.0             .15
6        VR     CELEC                                .001
7        VI     SELEC                                .001
8        VI     SELEC              900.0             .15
9        VRT    CCAP                                 .7
10       VRT    RF                                   2.5
11       RF     CELEC                        7.
12       RF     CELEC              100.
13       VIT    VI                           500.
14       VIT    SELEC              6.3       280.   .7
15       VIT    SCAP                                 .7
16       VIT    IF                                   2.5
17       IF     SELEC              7.
18       IF     SELEC              100.
19       CCAP                                  5.
20       SCAP                                  5.
21       CCAP   CELEC              .01
22       SCAP   SELEC              .01
23       CELEC                     .43       22.
24       SELEC                     .43       22.
25       CAN    CGR                          1.
26       SAN    SGR                          1.
27       CGR    CELEC                        1.
28       SGR    SELEC                        1.
29       CGR                                          .06
30       SGR                                          .06
31       F      SW                 5.00
32     -1VRT    F                  .02       2.2     .0173  150.
33     -1F      VIT                .02       2.2     .0173  700.
34
35       SW                  1.E-2  1.
36
37     16VR     1  1.39     133000.          4.4       0.04      0.0103     900.
38     16CAN       -148000.   14900.        -120000.   146000.
39     16SAN    3  1.39      800.0000        4.6       0.03      0.0125     900.
40     16VI        -148000.   14800.        -117700.   -10000.
41
42       VRT    VR     VIT    VI
43
44
45
46
```

(b) Detailed Model

```
1    PACIFIC HV-DC INTERTIE                                                  2
2        40.E-6     75.E-3  1      1          0                          1
3      GENAS BIGEA                    .01
4      GENBS BIGEB GENAS BIGEA
5      GENCS BIGEC GENAS BIGEA
6      BIGEA                          .86   114.   2.46
7      BIGEB       BIGEA
8      BIGEC       BIGEA
9              BIGEA                 1.18  114.   1.28
10             BIGEB       BIGEA
11             BIGEC       BIGEA
12     BIGEA CETA                     .02   1.56
13     BIGEB CETB  BIGEA CETA
14     BIGEC CETC  BIGEA CETA
15     CETA  CHPA                    40.
16     CHPA  CETA                          5.5
17     CETB  CHPB  CETA  CHPA
18     CHPB  CHTB  CHPA  CETA
19     CETC  CHPC  CETA  CHPA
20     CHPC  CETC  CHPA  CETA
21     CHPA                                      3.9
22     CHPB        CHPA
23     CHPC        CHPA
24             CETA                  .93   44.    .95
25             CETB        CETA
26             CETC        CETA
27     CETA  C11A  GENAS BIGEA
28     CETB  C11B  GENAS BIGEA
29     CETC  C11C  GENAS BIGEA
30     C11A                          .82   44.    1.33
31     C11B        C11A
32     C11C        C11A
33     C11A  CTXAP                   .22   2.07
34     C11B  CTXBP C11A  CTXAP
35     C11C  CTXCP C11A  CTXAP
36    51CTXAP                              99300.
37    52CTXAS NS                           47951.          23174.
38     1CTXBP       CTXAP
39     2CTXBS NS
40     1CTXCP       CTXAP
41     2CTXCS NS
42      NS                           1.E+10
43     CTXAS CVDA                    .07    8343
44     CTXBS CVDB  CTXAS CVDA
45     CTXCS CVDC  CTXAS CVDA
46     CEL   CVDA                   1200.  0.0    .1
47     CEL   CVDB  CEL   CVDA
48     CEL   CVDC  CEL   CVDA
49     CAN   CVDA  CEL   CVDA
50     CAN   CVDB  CEL   CVDA
51     CAN   CVDC  CEL   CVDA
52     CVDA  CCA                    1000.
53     CCA   CVDA                          .25
54     CVDB  CCB   CVDA  CCA
55     CCB   CVDB  CCA   CVDA
56     CVDC  CCC   CVDA  CCA
57     CCC   CVDC  CCA   CVDA
58     CIR1  CCTH                    .01
59     CIR3  CCTH  CIR1  CCTH
60     CIR5  CCTH  CIR1  CCTH
```

```
 61        CEL     CCTH    CVDA    CCA
 62        CCTH    CEL     CCA     CVDA
 63        CD1     CCA                     3000.
 64        CCA     CD1                             1.0
64.2       CEL     CAN                     1.E20
64.4       SAN     SCTH                    1.E20
 65        CD3     CCB     CD1     CCA
 66        CCB     CD3     CCA     CD1
 67        CD5     CCC     CD1     CCA
 68        CCC     CD5     CCA     CD1
 69        CD4     CAN     CD1     CCA
 70        CAN     CD4     CCA     CD1
 71        CD6     CAN     CD1     CCA
 72        CAN     CD6     CCA     CD1
 73        CD2     CAN     CD1     CCA
 74        CAN     CD2     CCA     CD1
 77        CAN     CGR                             1.0
 78        CGR     CELEC   CAN     CGR
 79        CGR                                             .06
 80       1CELEC                           .43     22.     .000
 81        CEL     POLES                           500.0
 82        POLES   CELEC                   6.3     280.    .7
 83        POLES   HPS                                     2.5
 84        HPS     CELEC                   100.
 85        CELEC   HPS                             7.0
 86        POLES   SURCS                                   .7
 87        SURCS                                           5.
 88        SURCS   CELEC   GENAS   BIGEA
 89       -1POLESSFAULT                    .02     2.2     .0173 150.
 90       -1FAULT POLERR                   .02     2.2     .0173 700.
 91        SAN     SYL     CEL     POLES
 92        POLER   SELEC   POLES   CELEC
 93        POLER   HPR     POLES   HPS
 94        HPR     SELEC   HPS     CELEC
 95        SELEC   HPR     CELEC   HPS
 96        POLER   SURCR   POLES   SURCS
 97        SURCR           SURCS
 98        SURCR   SELEC   GENAS   BIGEA
 99        POLER   CAP     GENAS   BIGEA
100        CAP                                             .06
101        CAP     SYL                             1.0
102        STA     LA                              1.0
103        STB     LB      STA     LA
104        STC     LC      STA     LA
105        LA                                              .06
106        LB              LA
107        LC              LA
108        LA      S57A    GENAS   BIGEA
109        LB      S57B    GENAS   BIGEA
110        LC      S57C    GENAS   BIGEA
111        S57A                    4.0     214.    1.32
112        S57B            S57A
113        S57C            S57A
114                S57A                    5.7     214.    .67
115                S57B            S57A
116                S57C            S57A
117        S57A    S13A    GENAS   BIGEA
118        S57B    S13B    GENAS   BIGEA
119        S57C    S13C    GENAS   BIGEA
120        S13A                    1.8     44.     1.33
```

121		S13B		S13A				
122		S13C		S13A				
123			S13A			2.2	44.	.95
124			S13B		S13A			
125			S13C		S13A			
126		S13A	SHPA			34.5		
126.2		SW				5		
127		SHPA	S13A				4.8	
128		SHPA						4.5
128.1		CD1	CIR1					.001
128.11		CD3	CIR3	CD1	CIR1			
128.12		CD5	CIR5	CD1	CIR1			
128.13		CD4	CCA	CD1	CIR1			
128.14		CD6	CCB	CD1	CIR1			
128.15		CD2	CCC	CD1	CIR1			
129		S13B	SHPB	S13A	SHPA			
130		SHPB	S13B	SHPA	S13A			
131		SHPB		SHPA				
132		S13C	SHPC	S13A	SHPA			
133		SHPC	S13C	SHPA	S13A			
134		SHPC		SHPA				
135		S13A	GENAR	GENAS	BIGEA			
136		S13B	GENBR	GENAS	BIGEA			
137		S13C	GENCR	GENAS	BIGEA			
138		STA	STXAP	C11A	CTXAP			
139		STB	STXBP	C11A	CTXAP			
140		STC	STXCP	C11A	CTXAP			
141		1STXAP		CTXAP				
142		2STXAS	NR					
143		1STXBP		CTXAP				
144		2STXBS	NR					
145		1STXCP		CTXAP				
146		2STXCS	NR					
147		NR		NS				
148		STXAS	SVDA	CTXAS	CVDA			
149		STXBS	SVDB	CTXAS	CVDA			
150		STXCS	SVDC	CTXAS	CVDA			
151		SAN	SVDA	CEL	CVDA			
152		SAN	SVDB	CEL	CVDA			
153		SAN	SVDC	CEL	CVDA			
154		SCTH	SVDA	CEL	CVDA			
155		SCTH	SVDB	CEL	CVDA			
156		SCTH	SVDC	CEL	CVDA			
157		SIR2	SCTH	CIR1	CCTH			
158		SIR6	SCTH	CIR1	CCTH			
159		SIR4	SCTH	CIR1	CCTH			
160		SAN	SD1	CD1	CCA			
161		SD1	SAN	CCA	CD1			
162		SAN	SD3	CD1	CCA			
163		SD3	SAN	CCA	CD1			
164		SAN	SD5	CD1	CCA			
165		SD5	SAN	CCA	CD1			
166		SVDA	SD4	CD1	CCA			
167		SD4	SVDA	CCA	CD1			
168		SVDB	SD6	CD1	CCA			
169		SD6	SVDB	CCA	CD1			
170		SVDC	SD2	CD1	CCA			
171		SD2	SVDC	CCA	CD1			
171.03		CCA	CCAII			.01		
171.06		CCB	CCBII			.01		

```
171.09     CCC    CCCII                .01
171.12     SVDA   SVDAII               .01
171.15     SVDB   SVDBII               .01
171.18     SVDC   SVDCII               .01
171.3      CCAI                        87.22  112.94
171.6      CCBI                        87.22  112.94
171.9      CCCI                        87.22  112.94
172.2      SVDAI                       -73.24125.14
172.5      SVDBI                       -73.24125.14
172.8      SVDCI                       -73.24125.14
174        SCTH   SGR    CAN    CGR
175        SGR    SELEC  CAN    CGR
176        SGR           CGR
177       1SELEC         CELEC
178
179      -1CIR1   CD1     0.0
180      -1CIR3   CD3
181      -1CIR5   CD5
182      -1CCA    CD4
183      -1CCB    CD6
184      -1CCC    CD2     0.0
186      -1SVDA   SD1
187      -1SVDB   SD3     0.0
188      -1SVDC   SD5     0.0
189      -1SIR4   SD4     0.0
190      -1SIR6   SD6
191      -1SIR2   SD2
191.02     CCAII  CCAI   -1.                                  1.E10
191.04     CCBII  CCBI   -1.                                  1.E10
191.06     CCCII  CCCI   -1.                                  1.E10
191.08     SVDAIISVDAI   -1.                                  1.E10
191.1      SVDBIISVDBI   -1.                                  1.E10
191.12     SVDCIISVDCI   -1.                                  1.E10
191.2    16          4   1.39    133000.      4.4      0.04    .0103    900.
191.23                  -148000. 14800.    -120000.  146000.   60.
191.26     C11A   C11B   C11C               7.18996
191.29   16        -6    1.39    +735.00      4.6      0.03    .0125    900.
191.32                  -148000. 14800.    -117700.  -10000.   60.
191.35     STA    STB.   STC                7.18996
191.5      POLES  POLESS -1.          1.5
192        POLER  POLERR -1.          1.5
192.2      FAULT  SW       .01        1.5
193
194      14GENAS    191880.   60.       -60.                          -1.
195      14GENBS    191880.   60.       180.                          -1.
196      14GENCS    191880.   60.       +60.0                         -1.
197      14GENAR    177000.   60.       -60.                          -1.
198      14GENBR    177000.   60.       180.                          -1.
199      14GENCR    177000.   60.       +60.0                         -1.
200
200.05    2CCTH   133000.
200.1     2CEL    133000.
200.15    2POLES  133000.
200.2     2POLESS133000.
200.25    2FAULT  130300.
200.3     2POLERR117700.
200.35    2POLER  117700.
200.4     2CAP    117700.
200.405   2SCTH   387.
200.41    2SGR    387.
```

```
200.415  2SELEC 387.
200.42   2CELEC -387.
200.425  2CGR   -387.
200.43   2CAN   -387.
200.45   2SYL   117700.
200.5    2SAN   140350.
200.52   3SAN   SVDA
200.525  3SAN   SVDB                    140350.
200.53   3SAN   SVDC
200.55   3CEL   POLES 900.
200.6    3POLESSFAULT 900.                          -900.
200.65   3FAULT POLERR900.                          -900.
200.7    3POLER CAP   900.
200.71   3CAP   SYL   900.
200.72   3CAP                           117700.
200.73   3CELEC HPS
200.74   3SELEC HPR
200.75   3POLES SURCS                   133000.
200.76   3POLER SURCR                   117700.
200.77   3POLES HPS                     133000.
200.78   3POLER HPR                     117700.
200.79   3POLES CELEC                   133000.
200.791  3CELEC       -900.
200.792  3SELEC        900.
200.793  3CAN   CGR   -900.
200.794  3CGR   CELEC -900.
200.795  3CGR
200.796  3SCTH  SGR    900.
200.797  3SGR   SELEC  900.
200.798  3SGR
200.8    3POLER SELEC                   117700.
200.81   3SAN   SYL   -900.
200.82   3CCTH  CEL    900.
201       CEL   SAN
202
203
```

APPENDIX 6

Sample Data Deck of the Three-Terminal Operation Simulation

```
PACIFIC HV-DC INTERTIE                                                    0
   60.E-6   98.8E-3 -1        1          0                               1
GENAS BIGEA                .01
GENBS BIGEB GENAS BIGEA
GENCS BIGEC GENAS BIGEA
BIGEA                      .86   114.   2.46
BIGEB       BIGEA
BIGEC       BIGEA
      BIGEA                1.18  114.   1.28
      BIGEB        BIGEA
      BIGEC        BIGEA
BIGEA CETA                 .02   1.56
BIGEB CETB  BIGEA CETA
BIGEC CETC  BIGEA CETA
CETA  CHPA                 40.
CHPA  CETA                       5.5
CETB  CHPB  CETA  CHPA
CHPB  CETB  CHPA  CETA
CETC  CHPC  CETA  CHPA
CHPC  CETC  CHPA  CETA
CHPA                                   3.9
CHPB        CHPA
CHPC        CHPA
      CETA                 .93   44.    .95
      CETB         CETA
      CETC         CETA
CETA  C11A  GENAS BIGEA
CETB  C11B  GENAS BIGEA
CETC  C11C  GENAS BIGEA
C11A                       .82   44.    1.33
C11B        C11A
C11C        C11A
C11A  CTXAP                .22   2.07
C11B  CTXBP C11A  CTXAP
C11C  CTXCP C11A  CTXAP
51CTXAP                          99300.
52CTXAS NS                       47951.              23174.
 1CTXBP        CTXAP
 2CTXBS NS
 1CTXCP        CTXAP
 2CTXCS NS
 CTXAS CVDA                .07   .8343
 CTXBS CVDB  CTXAS CVDA
 CTXCS CVDC  CTXAS CVDA
 CEL   CVDA                1200. 0.0    .1
 CEL   CVDB  CEL   CVDA
 CEL   CVDC  CEL   CVDA
 CAN   CVDA  CEL   CVDA
 CAN   CVDB  CEL   CVDA
 CAN   CVDC  CEL   CVDA
 CVDA  CCA                 1000.
 CCA   CVDA                       .25
 CVDB  CCB   CVDA  CCA
 CCB   CVDB  CCA   CVDA
 CVDC  CCC   CVDA  CCA
 CCC   CVDC  CCA   CVDA
 CIR1  CCTH                .01
 CIR3  CCTH  CIR1  CCTH
 CIR5  CCTH  CIR1  CCTH
 CEL   CCTH  CVDA  CCA
```

```
62        CCTH  CEL   CCA   CVDA
63        CD1   CCA                3000.
64        CCA   CD1                      1.0
67        CD3   CCB   CD1   CCA
68        CCB   CD3   CCA   CD1
69        CD5   CCC   CD1   CCA
70        CCC   CD5   CCA   CD1
71        CD4   CAN   CD1   CCA
72        CAN   CD4   CCA   CD1
73        CD6   CAN   CD1   CCA
74        CAN   CD6   CCA   CD1
75        CD2   CAN   CD1   CCA
76        CAN   CD2   CCA   CD1
77        CAN   CGR                      1.0
78        CGR   CELEC CAN   CGR
79        CGR                                .06
80       1CELEC                    .43   22.
81        CEL   POLES                    500.0
81.2      SW11  POLERR                   .015
81.4      SW11  SW11I GENAS BIGEA
81.5      SW12  SW12I GENAS BIGEA
82        POLES CELEC              6.3   280.   .7
83        POLES HPS                            2.5
84        HPS   CELEC             100.
85        CELEC HPS                      7.0
86        POLES SURCS                          .7
87        SURCS                                5.
88        SURCS CELEC GENAS BIGEA
89      -1POLESSFAULT3             .015  4.27  .0142 600.
89.2    -2POLE4 FAULT4             .02   1.56  .0192 600.
90      -1FAULT3POLERR             .015  4.27  .0142 250.
90.2    -2FAULT4SW12               .02   1.56  .0192 250.
91        SAN   SYL   CEL   POLES
92        POLER SELEC POLES CELEC
92.02     GENAS BIGEAAGENAS BIGEA
92.04     GENBS BIGEBAGENAS BIGEA
92.06     GENCS BIGECAGENAS BIGEA
92.08     BIGEAA      BIGEA
92.1      BIGEBA      BIGEA
92.12     BIGECA      BIGEA
92.122          BIGEAA      BIGEA
92.124          BIGEBA      BIGEA
92.126          BIGECA      BIGEA
92.14     BIGEAACETAA BIGEA CETA
92.16     BIGEBACETBA BIGEA CETA
92.18     BIGECACETCA BIGEA CETA
92.2      CETAA CHPAA CETA  CHPA
92.22     CETBA CHPBA CETA  CHPA
92.24     CETCA CHPCA CETA  CHPA
92.26     CHPAA CETAA CHPA  CETA
92.28     CHPBA CETBA CHPA  CETA
92.3      CHPCA CETCA CHPA  CETA
92.32     CHPAA       CHPA
92.34     CHPBA       CHPA
92.36     CHPCA       CHPA
92.38           CETAA       CETA
92.4            CETBA       CETA
92.42           CETCA       CETA
92.44     CETAA C11AA CETA  C11A
92.46     CETBA C11BA CETA  C11A
```

```
 92.48    CETCA C11CA CETA  C11A
 92.5     C11AA       C11A
 92.52    C11BA       C11A
 92.54    C11CA       C11A
 92.56    C11AA CTXPA C11A  CTXAP
 92.58    C11BA CTXPB C11A  CTXAP
 92.6     C11CA CTXPC C11A  CTXAP
 92.62   1CTXPA       CTXAP
 92.64   2CTXSA ANS
 92.66   1CTXPB       CTXAP
 92.68   2CTXSB ANS
 92.7    1CTXPC       CTXAP
 92.72   2CTXSC ANS
 93       POLER HPR   POLES HPS
 93.1     ACTH  AGR.  CAN   CGR
 93.15    AGR         CGR
 93.2     AGR   CELEC CAN   CGR
 93.3     AAN   ACEL  GENAS BIGEA
 93.35    ACEL  POLA  CEL   POLES
 93.4     POLA  CELEC POLES CELEC
 93.45    POLA  AHPS  POLES HPS
 93.5     AHPS  CELEC HPS   CELEC
 93.55    CELEC AHPS  CELEC HPS
 93.6     POLA  ASUR  POLES SURCS
 93.65    ASUR        SURCS
 93.7     ASUR  CELEC GENAS BIGEA
 94       HPR   SELEC HPS   CELEC
 95       SELEC HPR   CELEC HPS
 96       POLER SURCR POLES SURCS
 97       SURCR       SURCS
 98       SURCR SELEC GENAS BIGEA
 99       POLER CAP   GENAS BIGEA
100       CAP                      .06
100.2     CTXSA AVDA  CTXAS CVDA
100.4     CTXSB AVDB  CTXAS CVDA
100.6     CTXSC AVDC  CTXAS CVDA
101       CAP   SYL                1.0
101.05    AAN   AVDA  CEL   CVDA
101.1     AAN   AVDB  CEL   CVDA
101.15    AAN   AVDC  CEL   CVDA
101.2     ACTH  AVDA  CEL   CVDA
101.25    ACTH  AVDB  CEL   CVDA
101.3     ACTH  AVDC  CEL   CVDA
101.35    AVDA  ACCA  CVDA  CCA
101.4     AVDB  ACCB  CVDA  CCA
101.45    AVDC  ACCC  CVDA  CCA
101.5     ACCA  AVDA  CCA   CVDA
101.55    ACCB  AVDB  CCA   CVDA
101.6     ACCC  AVDC  CCA   CVDA
101.65    ACIR4 ACTH  CIR1  CCTH
101.67    ACIR6 ACTH  CIR1  CCTH
101.69    ACIR2 ACTH  CIR1  CCTH
101.71    AAN   ACD1  CD1   CCA
101.73    AAN   ACD3  CD1   CCA
101.75    AAN   ACD5  CD1   CCA
101.77    ACCA  ACD4  CD1   CCA
101.79    ACCB  ACD6  CD1   CCA
101.81    ACCC  ACD2  CD1   CCA
101.83    ACD1  AAN   CCA   CD1
101.85    ACD3  AAN   CCA   CD1
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101.87	ACD5	AAN	CCA	CD1			
101.89	ACD4	ACCA	CCA	CD1			
101.91	ACD6	ACCB	CCA	CD1			
101.93	ACD2	ACCC	CCA	CD1			
102	STA	LA				1.0	
103	STB	LB	STA	LA			
104	STC	LC	STA	LA			
105	LA						.06
106	LB		LA				
107	LC		LA				
108	LA	S57A	GENAS	BIGEA			
109	LB	S57B	GENAS	BIGEA			
110	LC	S57C	GENAS	BIGEA			
111	S57A				4.0	214.	1.32
112	S57B		S57A				
113	S57C		S57A				
114		S57A			5.7	214.	.67
115		S57B		S57A			
116		S57C		S57A			
117	S57A	S13A	GENAS	BIGEA			
118	S57B	S13B	GENAS	BIGEA			
119	S57C	S13C	GENAS	BIGEA			
120	S13A				1.8	44.	1.33
121	S13B		S13A				
122	S13C		S13A				
123		S13A			2.2	44.	.95
124		S13B		S13A			
125		S13C		S13A			
126	S13A	SHPA			34.5		
127	SW				5.		
128	SHPA	S13A				4.8	
129	SHPA						4.5
130	S13B	SHPB	S13A	SHPA			
131	SHPB	S13B	SHPA	S13A			
132	SHPB		SHPA				
133	S13C	SHPC	S13A	SHPA			
134	SHPC	S13C	SHPA	S13A			
135	SHPC		SHPA				
142	S13A	GENAR	GENAS	BIGEA			
143	S13B	GENBR	GENAS	BIGEA			
144	S13C	GENCR	GENAS	BIGEA			
145	STA	STXAP	C11A	CTXAP			
146	STB	STXBP	C11A	CTXAP			
147	STC	STXCP	C11A	CTXAP			
148	1STXAP		CTXAP				
149	2STXAS	NR					
150	1STXBP		CTXAP				
151	2STXBS	NR					
152	1STXCP		CTXAP				
153	2STXCS	NR					
155	STXAS	SVDA	CTXAS	CVDA			
156	STXBS	SVDB	CTXAS	CVDA			
157	STXCS	SVDC	CTXAS	CVDA			
158	SAN	SVDA	CEL	CVDA			
159	SAN	SVDB	CEL	CVDA			
160	SAN	SVDC	CEL	CVDA			
161	SCTH	SVDA	CEL	CVDA			
162	SCTH	SVDB	CEL	CVDA			
163	SCTH	SVDC	CEL	CVDA			
164	SIR2	SCTH	CIR1	CCTH			

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165         SIR6   SCTH   CIR1   CCTH
166         SIR4   SCTH   CIR1   CCTH
167         SAN    SD1    CD1    CCA
168         SD1    SAN    CCA    CD1
169         SAN    SD3    CD1    CCA
170         SD3    SAN    CCA    CD1
171         SAN    SD5    CD1    CCA
172         SD5    SAN    CCA    CD1
173         SVDA   SD4    CD1    CCA
174         SD4    SVDA   CCA    CD1
175         SVDB   SD6    CD1    CCA
176         SD6    SVDB   CCA    CD1
177         SVDC   SD2    CD1    CCA
178         SD2    SVDC   CCA    CD1
191         SCTH   SGR    CAN    CGR
192         SGR    SELEC  CAN    CGR
193         SGR           CGR
194        1SELEC         CELEC
194.05      CCAI                         59.93 296.
194.1       CCBI                         59.93 296.
194.15      CCCI                         59.93 296.
194.2       SVDAI                        -90.7 627.
194.25      SVDBI                        -90.7 627.
194.3       SVDCI                        -90.7 627.
194.35      ACCAI                        -99.3 618.
194.4       ACCBI                        -99.3 618.
194.45      ACCCI                        -99.3 618.
194.5       CCA    CCAII  GENAS  BIGEA
194.55      CCB    CCBII  GENAS  BIGEA
194.6       CCC    CCCII  GENAS  BIGEA
194.65      ACCA   ACCAIIGENAS  BIGEA
194.7       ACCB   ACCBIIGENAS  BIGEA
194.75      ACCC   ACCCIIGENAS  BIGEA
194.8       SVDA   SVDAIIGENAS  BIGEA
194.85      SVDB   SVDBIIGENAS  BIGEA
194.9       SVDC   SVDCIIGENAS  BIGEA
195
196       -1CIR1   CD1     0.0
197       -1CIR3   CD3
198       -1CIR5   CD5
199       -1CCA    CD4
200       -1CCB    CD6
201       -1CCC    CD2     0.0
202       -1SVDA   SD1
203       -1SVDB   SD3     0.0
204       -1SVDC   SD5     0.0
205       -1SIR4   SD4     0.0
206       -1SIR6   SD6
207       -1SIR2   SD2
207.005     CCAII  CCAI   -1.                          1.E10
207.01      CCBII  CCBI   -1.                          1.E10
207.015     CCCII  CCCI   -1.                          1.E10
207.02      SVDAIISVDAI   -1.                          1.E10
207.025     SVDBIISVDBI   -1.                          1.E10
207.03      SVDCIISVDCI   -1.                          1.E10
207.035     ACCAIIACCAI   -1.                          1.E10
207.04      ACCBIIACCBI   -1.                          1.E10
207.045     ACCCIIACCCI   -1.                          1.E10
207.1     -1ACCA   ACD1
207.2     -1ACCB   ACD3
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207.3    -1ACCC  ACD5
207.4    -1ACIR4 ACD4
207.5    -1ACIR6 ACD6
207.6    -1ACIR2 ACD2
214      16       2  1.39     800.000      4.6       0.03      .0125     700.
215                -148000.  14800.     -70000.0  79000.0    60.
216        C11A   C11B  C11C              7.18996
217      16       -1  1.39    -58000.      4.4       0.04      .0103     370.
218                -158000.  14800.     -80000.0  -10000.    60.
219        STA    STB   STC               7.18996
219.2    16       -1  1.39    -52500.      4.6       0.03      .0125     370.
219.4              -162000.  15300.     -120000.  -10000.    60.
219.6      C11AA C11BA C11CA              7.18996
220        POLES POLESS -1.        1.5
221        POLER POLERR -1.        1.5
221.2      POLE4 POLA   -1.        1.5
221.4      SW11I SW12I  -1         1.5
222        SW12  SW      .01       1.5
223
224      14GENAS    187770.   60.       -50.                          -1.
225      14GENBS    187770.   60.       -170.                         -1.
226      14GENCS    187770.   60.       +70.0                         -1.
227      14GENAR    177000.   60.       -50.                          -1.
228      14GENBR    177000.   60.       -170.                         -1.
229      14GENCR    177000.   60.       +70.0                         -1.
230
231        2CCTH  70000.
232        2CEL   70000.
233        2POLES 70000.
234        2POLESS70000.
235        2FAULT362370.
235.05     2FAULT456400.
235.1      2POLE4 52500.
235.15     2POLA  52500.
235.2      2ACEL  52500.
235.25     2SW11  58000.
235.255    2SW12I 58000.
235.27     2SW11I 58000.
235.3      2SW12  58000.
235.35     2AAN   52500.
235.4      2ACTH  -132.
235.45     2AGR   -132.
236        2POLERR58000.
237        2POLER 58000.
238        2CAP   58000.
239        2SCTH  132.
240        2SGR   132.
241        2SELEC 132.
242        2CELEC -132.
243        2CGR   -132.
244        2CAN   -132.
245        2SYL   58000.
246        2SAN   140350.
247        3SAN   SVDA
248        3SAN   SVDB
249        3SAN   SVDC
250        3CEL   POLES 640.
251        3POLESSFAULT3640.                          -640.
251.2      3POLE4 FAULT4-370.                         370.
252        3FAULT3POLERR640.                          -640.
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252.2    3FAULT4SW12  -370.                          370.
253      3POLER CAP    370.
254      3CAP   SYL    370.
255      3CAP                                 58000.
256      3CELEC HPS
257      3SELEC HPR
258      3POLES SURCS                         70000.
258.1    3POLA  ASUR                          52500.
258.2    3POLA  AHPS                          52500.
258.3    3POLA  CELEC                         52500.
258.4    3CELEC AHPS
259      3POLER SURCR                         58000.
260      3POLES HPS                           70000.
261      3POLER HPR                           58000.
262      3POLES CELEC                         70000.
263      3CELEC        -370.
264      3SELEC         370.
265      3CAN   CGR    -640.
266      3CGR   CELEC  -640.
266.1    3ACEL  POLA   -370.
266.2    3ACTH  AGR    370.
266.3    3AGR   CELEC  370.
266.4    3AGR
267      3CGR
268      3SCTH  SGR     370.
269      3SGR   SELEC   370.
270      3SGR
271      3POLER SELEC                         58000.
271.1    3SW11  POLERR -370.
271.2    3SURCS
271.3    3SURCR
271.4    3ASUR
272      3SAN   SYL    -370.
273      3CCTH  CEL     640.
274       SW11  POLE4  POLES
275
276
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