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INCLUDING ENERGY STORAGE

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CONTRACT ACTIVITY

The principal investigators have devoted 50% of their workload to this contract since October. This is expected to continue through the first half of 1978.

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ABSTRACT

Energy Storage

Work has continued on the development and verification of simplified analytical models for force-commutated converter (FCC) circuits used to interface superconducting magnets and storage batteries with a three-phase power network. The simplified model developed for the current-fed FCC is presently being verified using detailed computer simulations of an inductor-converter (IC) unit interfaced with a power system equivalent. A simplified model was also developed for a voltage-fed FCC to be used with storage batteries. The voltage-fed model has been verified through computer simulations, and is described in detail in the present report.

Work has also continued on the special work task involving the application of small IC units for system damping. This task involves the coordination of efforts at Purdue, Bonneville Power Administration, and Los Alamos Scientific Laboratories in order to design an experimental device to be installed on the BPA system. A progress report on this task is included herein as an Appendix.

Identification

Difficulty has been experienced in obtaining agreement between random signal covariances measured from an analog simulation and predicted analytically. The disparity appears to be due to insufficient noise generator output at low frequency, and should be resolved soon. A Kalman Filter algorithm has been implemented to process measurements from the analog simulation.

SECTION 1

SIMPLIFIED MODELS OF FORCE-COMMUTATED CONVERTERS

In the previous progress report C00-4206-2 a simplified analytical model was described in detail for a current-fed force commutated converter (CFFCC). This simplified model is suitable for control studies of inductor-converter (IC) units interfaced to a power system for purposes of energy storage and/or system damping. During the current period of investigation detailed computer simulations have been used for verification of the CFFCC simplified model. This work is still in progress and results will be included in the next regular report.

It was assumed that an impulse-commutated, voltage-fed force commutated converter (VFFCC) would be used to interface storage batteries with a power system. In the present report a simplified analytical model is described for this VFFCC type of interface. A detailed three-phase computer simulation was also developed for this type of converter. Computer simulations of a three-bus power system equivalent with both the simplified and detailed VFFCC representation were compared for verification of the simplified model.

1.1 Three-Phase Simulation

The detailed three-phase model of a VFFCC unit normally used for simulation is a generic model of the converter [1,2] since the ac voltage output of the converter is generated by applying a switching function to the converter's dc terminal voltage and a related switching function is used to generate dc current from ac phase currents. The switching functions are based on the assumption of instantaneous commutations which implies neglecting the effects of di/dt reactors. Although the effects of the commutation cir-

circuits and di/dt reactors can be superimposed on the ac voltages generated with switching functions that is generally not included in a simulation because of the large amount of additional simulation equipment required and the relatively small effects of the commutation circuits and di/dt reactors on the fundamental frequency component of the converters output. The generic simulation accounts for the interactions, including the major effects of harmonics, between the dc source and ac system.

Use of a VFFCC unit in applications where the magnitude relationship between the dc voltage and ac system voltage can change significantly requires some method of compensating for that change if satisfactory operation of the converter is to be realized. The voltage changes associated with the charge/discharge profile of batteries in energy storage applications are sufficiently large to require voltage matching compensation. The block diagram of Fig. 1.1 shows a system with a practical method of implementing voltage matching compensation between the dc source and ac system. The system includes two independently controlled twelve-pulse converters ($C_1 - C_2$ and $C_3 - C_4$) whose outputs are vectorially summed in the primary of the transformer as indicated in the phasor diagram of Fig. 1.2. The feedback signals (P_{ac} and Q) are calculated from the substation bus voltages (v_s) and converter transformer currents (i_T). The magnitude of the twelve-step converter output voltages ($v_1 + v_2$ and $v_3 + v_4$) are directly proportional to the converter dc voltage input but the action of the control loops regulates the combined converter system output voltage behind transformer impedance in magnitude and phase relationship to the substation bus voltage according to the equation:

$$v_c = kV_d / \theta + \phi + kV_d / \theta - \phi = 2kV_d \cos \phi / \theta$$

Fig. 1.1 Converter system block diagram.

Fig. 1.2 Phasor diagram of converter output.

The value of k is fixed by the transformer turns ratio. Its value should be determined from the minimum dc voltage, the maximum ac system voltage and the transformer impedance with some allowance for control responses.

1.2 Simplified Model

The simplified model of a VFFCC unit suitable for use with the simulation of an ac system in the synchronously rotating reference frame is developed in the following section. The amplitude of the converter bus voltage (v_s), defined as crest phase-to-neutral voltage, as shown in Fig. 1.3 is given by

$$v_s = \sqrt{v_{sq}^2 + v_{sd}^2} \quad (1.1)$$

$$\delta_c = \tan^{-1} \frac{-v_{sd}}{v_{sq}} \quad -180^\circ < \delta_c < 180^\circ \quad (1.2)$$

The phase reference for converter commutations as shown by Fig. 1.1 is derived from a variable frequency oscillator which is phase locked to the bus voltage and, during transients, it depends on the dynamics of the phase locked loop. An approximation to the dynamics of the phase lock control results in a converter commutation phase reference given by

Fig. 1.3 Reference frame phasor diagram.

$$\delta_{cc} = \delta_c \left(\frac{1}{T_a s + 1} \right) \left(\frac{1}{T_b s + 1} \right) \quad (1.3)$$

The converter's output voltage has a phase relationship defined by $\theta + \delta_{cc}$ with respect to the synchronously rotating reference frame. Therefore, in terms of reference frame quantities, the converter's voltage outputs are:

$$v_{cq} = v_c \cos(\theta + \delta_{cc}) = 2kV_d \cos \phi \cos(\theta + \delta_{cc}) \quad (1.4)$$

$$v_{cd} = -v_c \sin(\theta + \delta_{cc}) = -2kV_d \cos \phi \sin(\theta + \delta_{cc}) \quad (1.5)$$

The dc current for the converter in terms of reference frame currents is given by

$$I_d = i_{Tq} \cos(\theta + \delta_{cc}) - i_{Td} \sin(\theta + \delta_{cc}) \quad (1.6)$$

The converter control feedback signals in terms of reference frame quantities are given by

$$P_{ac} = v_{sq} i_{Tq} + v_{sd} i_{Td} \quad (1.7)$$

$$Q = v_{sq} i_{Td} - v_{sd} i_{Tq} \quad (1.8)$$

Those quantities represent real and reactive power flow from the converter to the converter bus.

The power input to the converter in terms of dc quantities is

$$P_{dc} = V_d I_d \quad (1.9)$$

The power calculated by equations 1.6 and 1.8 are expected to differ by any losses in the converter transformer.

The converter's dc terminal voltage is

$$V_d = \frac{1}{C_d} \int (I_b - I_d) dt \quad (1.10)$$

where I_b is the actual battery current.

The converter transformer currents in terms of reference frame quantities are

$$i_{Tq} = \frac{\omega}{X_L} (v_{cq} - v_{sq} - X_L i_{Td} - r_T i_{Tq}) dt \quad (1.11)$$

$$i_{Td} = \frac{\omega}{X_L} (v_{cd} - v_{sd} + X_L i_{Tq} - r_T i_{Td}) dt \quad (1.12)$$

The simplified model for a voltage fed force commutated converter is represented by Eqs. (1.1)-(1.12). Figure 1.4 shows the solution flow for the model. For a specific application the control transfer function and a dc source must be defined.

1.3 Computer Simulations

The validity of the simplified model was evaluated by comparing simulation results for a simplified model and a generic three-phase model of a voltage fed force commutated converter operating with detailed and simplified (reduced by reference frame theory) representations of the one-machine infinite bus system shown in Fig. 1.5. Reference frame theory reduces the sys-

Fig. 1.4 Block diagram of simplified model.

Fig. 1.5 Power system simulator.

tem to a simplified representation which is compatible with the simplified models of the storage units. The other computer simulation is a detailed three-phase representation of the system, which includes an individual valve representation of the converter. In both simulations, Park's equations are used to represent the synchronous machine. An IEEE Type 1 excitation system is used with the machine simulation.

In the simplified simulation of the system the transmission network, loads, and infinite bus are represented in the synchronously rotating reference frame, as are the simplified models of the IC and BC units. The machine is represented in a reference frame fixed in the rotor. If f^e is a variable in the synchronous frame and f^r is the same variable in the rotor reference frame, the transformation which relates the two representations is

$$\begin{bmatrix} f_q^e \\ f_d^e \end{bmatrix} = \begin{bmatrix} \cos \delta & \sin \delta \\ -\sin \delta & \cos \delta \end{bmatrix} \begin{bmatrix} f_q^r \\ f_d^r \end{bmatrix}$$

where δ is the rotor angle of the machine relative to the synchronous reference frame.

The per unit parameters for the 1000 MVA machine and ac system are listed below.

Machine

r_s = stator resistance	= 0.003 pu	x_{lkq} = q-axis damper leakage reactance	= 0.05233 pu
x_{ls} = stator leakage reactance	= 0.093 pu	r_{kd} = d-axis damper resistance	= 0.00789 pu
r_f = field resistance	= 0.00082 pu	x_{lkd} = d-axis damper leakage reactance	= 0.025 pu
x_{lf} = field leakage reactance	= 0.10746 pu	x_{mq} = q-axis magnetizing reactance	= 1.12 pu
r_{kq} = q-axis damper resistance	= 0.00759 pu	x_{md} = d-axis magnetizing reactance	= 1.44 pu
$H = 2.95$ sec.			

Machine Excitation (IEEE Type 1)

$K_A = 50$	$K_F = 0.013$	$V_{ref} = 1.0$ pu
$T_A = 0.02$ sec	$T_F = 0.38$ sec	$S_{EMAX} = 0.19$ pu
$K_E = -0.02$	$V_{RMAX} = 1.0$ pu	$S_{EMIN} = 0.08$ pu
$T_E = 0.08$ sec	$V_{RMIN} = -1.0$ pu	

Machine Transformer

$R_t = 0.01$ pu	$X_t = 0.1$ pu
-----------------	----------------

Transmission Network

$$\begin{aligned} v &= 1.0 \text{ pu} & R_2 &= 0.01 \text{ pu} & R_3 &= 0.05 \text{ pu} \\ R_1 &= 0.06 \text{ pu} & X_2 &= 0.1 \text{ pu} & X_3 &= 0.5 \text{ pu} \\ X_1 &= 0.6 \text{ pu} \end{aligned}$$

Loads

$$R_L = 2 \text{ pu} \quad X_L = 1 \text{ pu} \quad R = 10 \text{ pu} \quad X_C = 5 \text{ pu}$$

Parameters for the converter and its unit transformer based on the MVA rating of the converter are:

$$\begin{aligned} K_1 &= 2000 \text{ degrees/pu power} & K_2 &= 4000 \text{ degrees/pu var.} \\ T &= 2 \text{ sec.} & T_3 &= 4 \text{ sec.} \\ T_1 &= .05 \text{ sec.} & T_4 &= .1 \text{ sec.} \\ T_2 &= .25 \text{ sec.} & T_5 &= .5 \text{ sec.} \\ C_d &= 3000 \text{ pu.} \end{aligned}$$

Transformer

$$\begin{aligned} X_T &= 0.2 \text{ pu} & R_T &= 0.02 \text{ pu} \\ k &= 1.0 \end{aligned}$$

For the simplified model the dynamics of the phase lock control was represented by

$$\delta_{cc} = \frac{1}{.01s + 1} \frac{1}{.02s + 1} \delta_c$$

The equivalent circuit used for the battery is shown in Fig. 1.6. Parameter values are:

$$R_B = 0.1 \text{ pu} \quad L_B = .88 \times 10^{-6} \text{ pu}$$

Variables recorded during the computer studies include the following:

Fig. 1.6 Battery equivalent circuit.

T_e - Machine electrical torque

$\frac{\Delta\omega_r}{\omega_e}$ - Ratio of machine speed change to synchronous speed

δ - Machine rotor angle 1000 MVA base

E_x - Machine excitation

v_{ga} - Phase "a" machine terminal voltage

E_{gm} - Crest machine terminal voltage

v_a - Phase "a" converter bus voltage

E_m - Crest converter bus voltage

V_d - Converter dc terminal voltage

$\frac{\Delta\omega_l}{\omega_e}$ - Ratio of the change in output of phase lock control to synchronous speed

δ_c - Phase angle of converter bus voltages with respect to infinite bus

θ - Output of converter power regulator loop

α - Output of converter reactive power regulator loop

P_{ac} - Power flow to converter bus

Q - Reactive power flow to converter bus.

All variables except speeds and angles are in per unit. Machine and system variables are based on 1000 MVA and converter variables (V_d , I_b , P_{ac} and Q) are based on the converters rating. The recorded real power (P_{ac}) and reactive power (Q) signals were obtained via a transfer function $\frac{1}{0.1s+1}$ from the actual simulation variables for both simplified and detailed converter models. That was done to eliminate the harmonic components of the signals in the detailed simulation and allow a better comparison of the recorded quantities.

The initial runs made for comparison of the simplified and detailed converter models was with the converter transformer primary connected directly to an infinite bus. That was done to eliminate any assumptions made about the dynamics of the phase lock control and allow a direct comparison of the models. Figure 1.7 shows the result of a power reference step from zero to 1.0 pu discharging. There is no discernable difference in the two sets of traces except for battery current (I_b) which appears to be smaller for the detailed model. The difference can be accounted for by losses in the resistance of the converter transformer due to harmonics in the detailed model. The simplified model neglects the effects of harmonics. Figure 1.8 shows the effect of a step change in battery voltage from 1.0 to 0.9 pu with the converter power reference at zero. In both cases the battery current shows evidence of ringing which is caused by interaction between the voltage stiffening capacitor (C_d) at the converters dc terminals and the inductance of the converter transformer. The ringing is not readily apparent in the power (P_{ac}) and reactive power (Q) traces because the recorded variables are filtered. The results of those two runs and other runs not included in this report indicate the simplified model is an accurate representation except for the noted discrepancy in battery current. Since power and reactive power flow to the

Fig. 1.7 Step change in converter power reference (0 to -1.0 pu battery discharging).

(a) Detailed converter model (b) Simplified converter model

Fig. 1.8 Step change in battery voltage (1.0 to 0.9 pu) with converter power reference at zero.
 (a) Detailed converter model (b) Simplified converter model

converter bus is regulated by the converter controls any loss in the transformer resistance due to harmonics is forced to be reflected in the battery current in the detailed model whereas the simplified model neglects all harmonics. Figures 1.9 - 1.18 show the results of an ac system disturbance with (runs b and c) and without (run a) the converter in operation. Even numbered figures have no run "a" since the converter was not in operation. The synchronous machine speed ($\Delta\omega_b/\omega_e$) was repeated in both figures for a set of runs to provide a cross reference. Run "a" is for a detailed model of the ac system and runs "b" and "c" are for, respectively, detailed and simplified models of the ac system and converter. The studies have two objectives which are: (1) to compare the simplified and detailed models of the converter (the simplified and detailed models of the ac system are known to be identical) and (2) to investigate the capability of a VFFCC/battery system to provide damping for machine oscillations although the converters rating (70 MVA) is small compared to the generator rating (1000 MVA). The converter is controlled to provide machine damping by using the machines speed deviation from synchronous speed to modify the converter's power reference. The total power reference for the converter (fixed plus damping signal input) is limited to ± 1.0 pu. Although the power reference is limited to ± 1.0 pu, the converter power flow to the converter bus, which is being controlled can exceed either ± 1.0 pu during transients because of converter control dynamics.

Figures 1.9 and 1.10 show the results of energizing line 1 (see Fig. 1.5) with the ac system initially at steady state, generator input torque constant at zero and zero fixed power reference for the converter. Comparison of runs "b" and "c" show good agreement between the simplified and detailed models except for battery current (I_d), converter dc voltage (V_d) and to a lesser extent reactive power flow to the converter bus (Q). The difference in bat-

tery current (Fig. 1.9) was discussed previously and is primarily due to the additional losses in the transformer resistance due to the harmonics in the detailed model. The difference in converter dc voltage is due to the difference in battery current. The difference in reactive power (Fig. 1.10) may be partially due to differences in battery current and voltage but it is more likely due to differences in converter commutation reference represented by the dynamics of the phase lock control in the detailed model and the transfer function used to obtain δ_{cc} from δ_c (see Eq. 1.3). Comparison of the runs "b" and "c" to run "a" (Fig. 1.9) shows that the converter provided some damping for generator swings.

Figures 1.11 and 1.12 shows the results of a step change from zero to 0.8 pu in generator input torque, the converter's fixed power reference at zero and line 1 in service. Runs "b" and "c" in both figures show good agreement for the simplified and detailed converter models except for the expected difference in battery current (I_b) and converter dc voltage (V_d). Some difference can also be noted in reactive power (Q) but, generally, there is good agreement. Comparison of runs "b" and "c" to run "a" indicates more improvement in damping than for the disturbance created by switching line 1 with no input torque on the generator. That is partially true because the generator is less damped under load and there is more opportunity for the converter to have a damping effect.

Figure 1.13 and 1.14 show the results of a step change from zero to 0.8 pu in generator input torque, the converters fixed power reference at zero and line 1 out of service. The simplified (run b) and detailed (run c) models show good agreement except for the expected differences in battery current (I_b) and converter dc voltage (V_d). Comparison of runs "b" and "c" show that the converter has had a marked damping effect on generator oscillations. That is partially true because the generator is less damped with

line 1 out-of-service than with line 1 in-service as in the previous cases. However, the major reason is that the converter is in a better position to provide damping because of ac network configuration.

The difference in the runs in Figs. 1.15 and 1.16 and Figs. 1.17 and 1.18 is the value of the converters fixed power reference which is, respectively, at + 1.0 pu and -1.0 pu. Comparison of runs b and c from Figs. 1.13, 1.15 and 1.17 and runs a of those figures shows that the initial improvement in damping provided by the converter is approximately the same regardless of the converter's fixed power reference. However, during the final stages of the oscillations a smaller improvement in damping is apparent. The decrease in the converter's damping effect begins to occur when the damping signal fails to cause the converter's power flow (P_{ac}) to reach 1.0 pu in the direction opposite to that called for by the fixed power reference.

1.4 Conclusions

Comparison of results from simplified and detailed models of a VFFCC unit indicates that the simplified model would be adequate for control investigations. Differences noted between the two models were primarily in variables within the VFFCC/battery system and are adequately explained by losses associated with harmonics which are presented in the detailed model but are neglected in the simplified model. The studies conducted also indicated that a VFFCC/battery system can improve the damping in an ac system provided an appropriate damping signal is available for modifying the converters power reference. However, the studies also indicate that the improvement in damping is also dependent on the system configuration and the amount of damping already present in the system.

Fig. 1.9 Line 1 energized with generator torque fixed at zero and converter's fixed power reference at zero. (a) detailed ac system without converter (b) detailed ac system and converter (c) simplified ac system and converter.

Fig. 1.10 Line 1 energized with generator torque fixed at zero and converter's fixed power reference at zero. (b) detailed ac system and converter (c) simplified ac system and converter

Fig. 1.11 Step change in generator torque (0 to 0.8 pu) with line 1 in service and converters fixed power reference at zero. (a) detailed ac system without converter (b) detailed ac system and converter (c) simplified ac system and converter

Fig. 1.12 Step change in generator torque (0 to 0.8 pu) with line 1 in-service and converters fixed power reference at zero. (b) detailed ac system and converter (c) simplified ac system and converter

Fig. 1.13 Step change in generator torque (0 to 0.8 pu) with line 1 out-of-service and converter's fixed power reference at zero. (a) detailed ac system without converter (b) detailed ac system and converter (c) simplified ac system and converter.

Fig. 1.14 Step change in generator torque (0 to 0.8 pu) with line 1 out-of-service and converter's fixed power reference at zero. (b) detailed ac system and converter (c) simplified ac system and converter

Fig. 1.15 Step change in generator torque (0 to 0.8 pu) with line 1 out-of-service and converter's fixed power reference at 1.0 pu (discharging battery). (a) detailed ac system without converter (b) detailed ac system and converter (c) simplified ac system and converter

Fig. 1.16 Step change in generator torque (0 to 0.8 pu) with line 1 out-of-service and converter's fixed power reference at 1.0 pu (discharging battery). (b) detailed ac system and converter (c) simplified ac system and converter

Fig. 1.17 Step change in generator torque (0 to 0.8 pu) with line 1 out-of-service and converter's fixed power reference at 1.0 pu (charging battery). (a) detailed ac system without converter (b) detailed ac system and converter (c) simplified ac system and converter

Fig. 1.18 Step change in generator torque (0 to 0.8 pu) with line 1 out-of-service and converter's fixed power reference at 1.0 pu (charging battery). (b) detailed ac system and converter (c) simplified ac system and converter

1.5 References

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2. D.P. Carroll, P.C. Krause, G.E. Gareis, and C.M. Ong, "The Interaction of Electrical Distribution Systems with Batteries and Fuel Cells," EPRI Project 418 Final Report, May 1976.

SECTION 2

POWER SYSTEM IDENTIFICATION

This section of the progress report concerns identification of power system electromechanical models from system measurements, with only normal load variation present as a disturbing input.

2.1 Analog Simulation of a Random Process

It has previously been reported that an analog simulation of a one machine system with random load variation is in operation. Verification of the analog simulation, in terms of proper covariances of the various random signals, has not yet been achieved. It appears that the electronic noise generators employed are at fault. While the manufacturer's specification sheet claim true randomness down to "dc", it is evident that frequencies below 10 rad/s were not considered in the design. If this indeed proves to be the difficulty, it should be easily correctable, either by using a sample and hold device at the output of the electronic noise generator or by designing a routine so that the digital computer can generate an acceptably white noise. The routine presently provided by the system software appears to have too short a period of repetition.

2.2 Kalman Filtering for Reconstruction of the States

The power system identification problem presents itself somewhat differently from many other identification problems. Normally, a system model is formulated as

$$x_{k+1} = \Phi x_k + \Gamma u_k + D w_k$$

where x_k is the state vector at the k th time step, u_k is the input, and w_k is a random disturbance. Algorithms are designed for identification of matrices Φ and Γ , from measurements of system input and output, given that the matrix D is known [1]. In the language of transfer functions, the matrix Γ determines the "numerator dynamics". However, in the power system identification problem as formulated here, there is no measurable system input, only random disturbance. Thus the matrix D determines the "numerator", and is not known before the fact. It appears that many of the well known identification routines are not able to cope with this situation.

A type of algorithm that can work under this condition is one which employs a Kalman filter [2] to estimate states and predict system outputs, given the actual system outputs. The maximum likelihood algorithm is in this category. Essentially, a parameter guess establishes guesses of the system matrices (both Φ and D), and an accurate guess of the system parameters produces a Kalman filter that performs well. The penalty function to be minimized is based on the accuracy of system output predictions.

With this in mind, the implementation of discrete time Kalman filters has been studied. Specifically, a Kalman filter has been run using the one machine analog simulation. The driving signal for the filter is a measurement of current magnitude in the system's only "transmission line", as shown in Fig. 1.

Fig. 2.1 One machine system.

The filter equations are based on a simplified, reduced order model of the system. Performance of the filter is illustrated in Fig. 2. The random disturbance of the load is small enough that deviation in the machine speed and angle (top two traces) are not discernable by eye. Current magnitude deviations, the input to the filter, are on an expanded vertical scale in the third trace. The last trace is the filter's predictions of system output, based on a 140 millisecond time step. At the time this recording was made, the analog simulation was still not producing proper random signal covariances.

2.3 References

1. Saridis, "Stochastic Approximation Algorithms for Linear Discrete-Time System Identification," IEEE Trans., Vol. AC-13, October 1968.
2. Meditch, "Stochastic Optimal Linear Estimation and Control," McGraw-Hill, 1969.

Fig. 2.2 Performance of Kalman filter.

APPENDIX

Progress Report
on
SYSTEM DAMPING WITH IC UNITS

June 1, 1977 - December 1, 1977

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I. INTRODUCTION

Following the April 13, 1977 meeting at Purdue, it was decided by ERDA to increase the effort of the energy storage research contract at Purdue to include work in the application of small rating superconducting magnets (IC units) to damp power system oscillations. This was to be a combined effort with Bonneville Power Administration, Los Alamos Scientific Laboratory, Purdue University and Prof. H. A. Peterson acting as a consultant. Since the beginning of this work there has been an additional meeting at Portland. Dr. Carroll's letter of July 25, 1977 summarized the proceedings of this meeting. The work completed to date is discussed in this progress report and a tentative three month work schedule is given.

II. SIMPLIFIED MODELING AND PRELIMINARY DAMPING STUDIES OF AN IC UNIT

Following the April 13, 1977 meeting the one machine infinite bus system shown in Fig. 1 was simulated on the analog computer for the purposes of verifying the simplified representation of the IC unit and to perform preliminary damping studies. The results of this investigation are reported in the July 1977 Progress Report on "Security Assessment of Power Systems Including Energy Storage." Briefly, the validity of the simplified model and damping due to the IC unit (also BC unit) were investigated during and following a 0.25 sec. three phase fault. The machine selected was a 1000 MVA equivalent. Both 10 MW and 70 MW IC units were considered. A superconducting magnet was represented as a linear inductor and the damping control was a simple change of speed modulation of the power reference. Accuracy of the simplified model was verified by comparison with the computer response of a detailed representa-

tion of the IC unit. It was shown that both the 10 MW and 70 MW IC (and BC units) add damping to the system.

Fig. 1 Power System Studied.

III. DIGITAL PROGRAMS FOR LINEAR SYSTEM ANALYSIS

Following the July 20, 1977 meeting at BPA work was started at Purdue to develop digital programs which could be used to calculate root locus as well as the Bode and Nyquist plots of the system configurations shown in Fig. 2. The system shown in Fig. 2a is herein termed a voltage control system: the one in Fig. 2b a power control system. The transfer function (differentiator) between the AC-intertie current, Δi_{IT} , and frequency, $\Delta \omega$, was taken from [1 and 2]. The transfer function, $G(s)$, between the IC unit

(a)

(b)

Fig. 2 System Configurations.

(a) Voltage control

(b) Power control.

power, ΔP_{IC} , and ΔI_{IT} was to be determined from the time response trace of the AC intertie current during energization of the dynamic brake at Chief Joseph. The controller, $C_v(s)$ and $C_p(s)$ are to be designed from analysis of the linear system once $G(s)$ is known.

Since it was to be some time before $G(s)$ was computed by BPA a digital program was written by Purdue to calculate the Bode and Nyquist plots as well as the root locus of the configurations shown in Fig. 2 with the transfer function given in [2] used as $G(s)$. Simplified controllers were used for $C_v(s)$ and $C_p(s)$. The root locus, Bode and Nyquist plots were verified by comparison with the time response of the analog computer simulation of the systems. These programs may now be simply modified to accommodate the correct $G(s)$ which was supplied to Purdue in the latter part of November 1977 (See R.L. Cresap's letter of November 17, 1977).

IV. TRANSFER FUNCTION APPROACH

A three month work plan, starting December 1, 1977, for this phase of the project is shown in Fig. 3. Since there are several individuals and groups involved in this project and since there are a number of unknowns any projected work plan should be viewed as tentative.

Three controls or system configurations have been suggested; the one used in the simplified modeling studies (July 1, 1977 Progress Report) and the two given in Fig. 2. Within the next few weeks after this report has

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1. R.L. Cresap and W.A. Mittelstadt, "Small-Signal Modulation of the Pacific HVDC Intertie," IEEE Trans., Vol. PAS-95, No. 2, March/April 1976.
 2. R.L. Cresap, W.A. Mittelstadt, D.N. Scott and C.W. Taylor, "Modulation of the Pacific HVDC Intertie," Presented at the 1977 Spring Meeting of the Canadian Electrical Association.

reached BPA, LASL, and Prof. Peterson, each will be contacted for the purpose of deciding on configurations which should be considered initially. Once this is established, the digital computer programs for calculating the root locus, Bode and Nyquist plots will be modified to accept these configurations and the new $G(s)$ relating AC-intertie current to change in power at Chief Joseph ($\Delta I_{IT}/\Delta P_J$). An analog computer simulation will also be developed for each configuration.

Once the digital computer programs and the analog simulations are developed preliminary control studies will be conducted in preparation for the January meeting with BPA, LASL, and Prof. Peterson. At that time, the control design will be discussed in more detail and BPA will supply the information on noise characteristics of random load changes. The updated controller designs and the load change characteristics will then be incorporated into the digital and analog computer simulations and the initial design of the controller and IC units will be determined. It is assumed that the load change characteristics can be introduced in the system as a disturbance at Chief Joseph. Thus, the change in the power of the IC unit (ΔP_{IC}) in Fig. 2 will be added to the random load disturbances before $G(s)$.

Near the end of the initial design phase, information will be gathered from LASL and Prof. Peterson regarding the nonlinear operational characteristics of the IC unit of the size apparent from the linear design considerations. These properties as well as the nonlinear properties of a controller will be incorporated in the analog computer simulations and the design of the controller and IC unit for nonlinear operation will begin.

Fig. 3

Work Plan for
Transfer Function Analysis

Task	12/1/77	1/1/78	2/1/78	3/1/78
Modify digital programs and develop analog simulation for control configurations	////////////////////			
Controller and IC unit initial designs for linear operations		////////////////////		
Nonlinear operation including inductor and converter constraints and nonlinear controller operations			//////////////// +	
	↑ A	↑ B	↑ C	

A - Preliminary discussion of controller and system configurations.

B - 1 Information from BPA on noise characteristics of random load changes.

B - 2 Meeting with BPA, LASL, Purdue and Peterson to discuss details of linear controller design.

C - Information from LASL and Peterson regarding constraints on operation of IC unit.

V. EQUIVALENT SYSTEM APPROACH

As an effort in parallel with the transfer function approach, the system will be simulated in more detail on the analog computer. At this time it is considered possible to simulate the system as shown in Fig. 4. Here the northwest is represented by two equivalent machines; one at Chief Joseph and the other representing the remainder of the northwest system. The southwest is represented by a third equivalent generator. At the present time, three generators and the AC transmission system have been simulated on the analog computer using typical parameters. We have asked C.W. Taylor of BPA to furnish us with a three or four machine equivalent of the system which he feels would be a first approximation of the system parameters and configuration at the time the dynamic brake was energized. Once this information is received, we will incorporate this into the analog computer simulation.

Next, the energization of the dynamic brake will be simulated and the AC Intertie current will be monitored. The system parameters and configuration will then be modified as necessary to duplicate the current response obtained during the test. There are many unknowns: Is it necessary to represent the dynamics of the governors and excitation systems? If so, what parameters should be used? Will it be necessary to represent more than three machines? Can the AC and DC intertie be terminated at the same bus? How many and what type of random load characteristics should be incorporated? Here, information from BPA will be of utmost importance and hopefully the work being done under this contract by Prof. Triezenberg on parameter identification can be utilized to answer some of these questions.

Fig. 4 Equivalent System.

Since the approach and thus the outcome of this work is somewhat questionable, it is difficult to set forth a work plan in detail. However, preliminary indications as to the validity of this approach should be apparent within the next three months. If it is possible to duplicate the brake test with reasonable accuracy, then the equivalent system representation will be quite useful. First, it could be used to verify the IC unit design obtained by the transfer function approach. Next, the equivalent system representation could be used to determine the approximate system performance for load conditions other than those at the time of the brake test. This feature can be used to check the operation of the IC unit at various loads.

This work must be closely coordinated with BPA, particularly with R.L. Cresap and C.W. Taylor. Moreover, this work must be closely tied with the transfer function approach so that the results from each effort may be readily evaluated and appropriately incorporated.

VI. COMPLEMENTING RESEARCH

The purpose of undertaking this contract was to make use of the ongoing ERDA (DOE) research at Purdue. In this regard, the simplified models of the IC unit were developed and verified under the original contract. This material will now be made use of in the "Equivalent System Approach." Also, force commutated converters are presently being analyzed for the purpose of developing simplified models. Once these models are developed they will be employed to represent force commutated converters for possible use in IC units.