MASTER

SECURITY ASSESSMENT OF POWER SYSTEMS INCLUDING ENERGY STORAGE

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REA

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CONTRACT ACTIVITY

The principal investigators have devoted 50% of their workload to this contract during this quarter. D.M. Triezenberg will continue at 25% during the next quarter.

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ABSTRACT

Energy Storage

Work has continued on the simplified model of a current-fed, force-commutated converter (CFFCC) interface for systems with inductor-converter (IC) energy storage. A digital simulation has been developed to study in detail certain abnormal modes of operation for possible inclusion in the simplified CFFCC model.

Eigenvalue studies are being performed to aid in the formulation of energy storage control designs for dynamic stability applications. A computer simulation has been developed for a multi-machine power system, and is being used to study the effectiveness of real and reactive power modulation of energy storage in transient stability control.

The special task on the application of a small IC unit for damping of the BPA system has been completed. The control design has been verified by computer simulations, which use a measured transfer function approach as well as physically-based equivalent models.

Identification

Some errors in previous concepts of the system are discussed and efforts are re-directed. Results from a promising algorithm are shown.

SECTION 1

ENERGY STORAGE APPLICATIONS

1.1 Simplified CFFCC Model

During previous investigations involving inductor-converter (IC) applications using a current-fed, force-commutated converter (CFFCC) interface, it has been noted that the converter may operate in an abnormal "additional charging" mode. For power modulation applications this mode of operation occurs frequently at lagging power factors for practical sized commutating capacitors. Since the simplified model developed and verified earlier for the CFFCC is valid only for the normal mode of operation, efforts are now underway to extend the simplified analysis to include the "additional charging" mode.

The detailed analog computer simulation of the CFFCC circuit used in previous studies has limited application in abnormal modes of operation. It is valid only for a small portion of the "additional charging" region of operation. For this reason it was necessary to develop a digital program to simulate the dynamic behavior of the CFFCC circuit. This digital simulation, which can represent all modes of converter operation, runs nearly as fast as the earlier analog simulation of the CFFCC. It can be used separately or it can be interfaced with analog simulations of power networks via hybrid computer facilities. Presently it is being used as an aid in analyzing the "additional charging" region. Eventually the digital simulation will serve as a reference model for verification of future simplified models of the CFFCC.

1.2 Control Studies

In the area of dynamic stability assessment, eigenvalue studies are underway using linearized system models. This investigation uses a full

synchronous machine representation, including damper windings, linearized about the steady-state operating point. The converter is represented by its simplified model. A static (algebraic) representation is used for the transmission network. A modular approach is being used to organize the eigenvalue studies, so that systems of differing topologies may be investigated without extensive reprogramming. In this approach each power system component (subsystem) is formulated as an input-output block in terms of its own dynamics. The complete system is then assembled from the components through a linear connection matrix. Results from the eigenvalue studies should be helpful in identifying the critical states needed for feedback control design of energy storage units. It may also provide insight into further simplification of system models involving energy storage.

In the area of transient stability control, two basic methods of utilizing energy storage units are being considered. The first method is essentially the modulation of real power in a storage unit located at a generator bus. It appears that this direct approach may be controlled in a manner similar to a damping control, using the change in machine speed as a feedback control signal. The second method involves the control of the transmission network by reactive power modulation at intermediate buses. Both approaches require development of coordination techniques for multi-machine systems, and perhaps combinations of both methods could achieve the best overall control in a dispersed energy storage configuration. A computer simulation of a multi-machine system has been developed for this study. The simulation uses simplified machine and converter models, and a static representation of the transmission network.

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 as a disturbing input.

2.1 Reexamination of Past Assumptions

In the previous report, a maximum likelihood estimation scheme was described that was thought to have potential. Likelihood estimation requires knowledge of the a statistical distribution; in this case, it was thought that output autocorrelation estimates at various lags were jointly Gaussian. While each autocorrelation estimate is by itself Gaussian (by virtue of being the sum of many random variables from a fixed distribution), there is no basis for the joint distribution assumption. Thus the scheme proposed has no firm foundation.

A more serious error in thinking has been exposed, which has far reaching consequences for all schemes thus far considered. A presentation of the system equations aids in the explanation.

The linearized equations for the system are, in discrete time form, are

$$x_{k+1} = \Phi x_k + G w_k \quad (2.1)$$

$$y_k = C x_k + D w_k \quad (2.2)$$

In these equations, state vector x consists of speeds and angles for each generator, input vector w is a random walk load variation, and output vector y is power fluctuation measured on transmission lines. State transition matrix Φ depends on generator inertia and damping and on the system nodal admittance matrix with load buses eliminated. Output matrix

C depends on the nodal admittance matrix with load buses eliminated. Matrices G and D, however, are derived from the system nodal admittance matrix with load buses included, as they account for the effect of load fluctuation on machine motion and on line power fluctuation, respectively.

It had been thought that since the load fluctuations could be considered independent (over a period of a few minutes), the net effect of load fluctuation would be that of a scalar random walk. That is, w_k would be a scalar and G and D then would be vectors. It is now recognized that this simplification cannot be made.

This realization has redirected the effort into estimating matrices Φ and C, without regard for H and D. Several factors help influence this decision:

1. This project concerns identification of equivalents for "on-line" transient stability evaluation. A system model with load buses eliminated is appropriate for this purpose. Loads can be considered to be at the generation buses for a transient stability calculation. Estimation of Φ and C contributes to the development of such a model, while estimation of D and H does not.
2. A variety of reasonable assumptions about the load model lead to various G and H matrices, but practically the same Φ and C matrices.
3. An algorithm for estimation of Φ and C alone, regardless of the size of vector w_k , is available for the single output case.

2.2 Estimation of Φ and C

The Instrument Variable approach [1] allows estimation of the AR parameters of an ARMA discrete time transfer function from output measurements alone. This is equivalent to estimation of Φ and C for a single

output system in phase variable canonical form.

A recursive algorithm for this type of estimation has been programmed and used to estimate parameters of some simple transfer functions that were implemented with analog equipment. So far, some biases in the estimates appear to exist, but this may be due to an implementation error.

Figure 2.1 shows the operation of the recursive estimator when the transfer function is of the form

$$\frac{y(s)}{w(s)} = \frac{\omega^2}{s^2 + 2\alpha s + \alpha^2 + \omega^2} + 1$$

The discrete time equivalent of this is

$$\frac{y(z)}{w(z)} = \frac{p_2(z^{-1})}{z^{-2} + \phi_2 z^{-1} + \phi_1}$$

where $p_2(z^{-1})$ is a second order polynomial in z^{-1} . Coefficients ϕ_1 and ϕ_2 are related to α and ω by

$$\phi_1 = \exp(-2\alpha T)$$

$$\phi_2 = -2\exp(-\alpha T) \cos(\omega T)$$

For $\alpha = 1.5$, $\alpha^2 + \omega^2 = 80$, the discrete transfer function parameters should be $\phi_1 = .7408$, $\phi_2 = .3618$ for T (sample period) of 0.1 second. The run shown in Fig. 2.1 gave $\phi_1 = .6957$, $\phi_2 = .3253$ after 2432 samples.

It is somewhat remarkable that algorithm convergence is obtained when the system input and output are virtually indistinguishable by eye (refer to Fig. 2.1).

If the appearance of bias in the single output algorithm can be

Fig. 2.1 Operation of on-line estimator.

resolved, effort will be placed on obtaining a canonical form from which multiple output system parameters can be estimated.

References

1. P.C. Young, "An instrument variable method for real-time identification of a noisy process", Automatica, Vol. 6, pp. 271-287.

SECTION 3

EQUIVALENT MODEL FOR WEST COAST POWER SYSTEM

3.1 Introduction

A second method of developing a physically based equivalent model of the West Coast power system is presented. This equivalent system is used to verify the compensator design developed using the transfer function approach. From this work and the work reported earlier it appears that the compensator designed by BPA can be used with an IC unit to damp power system oscillations effectively.

3.2 Background

Since beginning of the work on power system damping with an IC unit in June of 1977, there has been an attempt to model the West Coast power system by an equivalent physically based model as an effort in parallel with the transfer function approach. In December, 1977, Mr. C.W. Taylor of BPA supplied a simplified equivalent of the West Coast system as it was thought to exist at the time the dynamic brake was energized at the Chief Joseph bus in June 1977. The single line diagram of this equivalent system is given in Fig. 3.1. This figure was also given in Progress Reports C00-4206-4, April 1978 and C00-4206-5, July 1978.

The first attempt to develop an equivalent system representation was reported in Progress Report C00-4206-5, July 1978. This equivalent, shown in Fig. 3.2, was established from the equivalent given by BPA (Fig. 3.1). It was thought that the three machine system (Fig. 3.2) might suffice. The three machines were represented in detail using

Park's equations with the machine parameters selected based upon the power delivered and the predominate type of area generation (hydro or steam). External damping was incorporated in the machine representation. This damping was varied on each machine in a trial and error approach to duplicate the time response of the AC Intertie current magnitude or power recorded during the brake test. Single time constant voltage regulators were represented. All loads were represented as constant power loads and the application and removal of the brake was represented by appropriate changes in P_1 (Fig. 3.2). The IC unit was represented by adjusting the reference power of the regulated power load P_1 . The load P_2 includes the DC Intertie power flow, assumed constant during the brake test.

There was found to be a reasonable agreement between the time response of the AC Intertie current magnitude obtained from the computer representation of the equivalent system, which was arrived at by trial and error, and that during actual brake test. (See pp. 25-28 of Progress Report C00-4206-5, July 1978). However, when the IC unit was incorporated for the purpose of providing power system damping, the required compensator gain was 10 times less than that obtained from the earlier work using the transfer function approach (Progress Report C00-4206-4, April 1978). It has since been determined that this difference in gain was due to an error of the simulation of the physically based equivalent model.

3.3 System Equivalencing by Frequency Response

The development of a physically based equivalent system model that matches the response of a power system is an end that can be attempted by various means. One means is the trial and error parameter

adjustment of an analog simulation that has already been described (Progress Report C00-4206-5, July 1978). It was felt that an automated procedure might yield an improved model and so another procedure was devised, giving another physically based model.

This procedure depends on the system frequency response calculated by BPA from the Chief Joseph brake test time response. A computer routine was first written which determines the small signal response of an arbitrary power system from fundamental parameters such as inertia, reactance, and loading. The routine assembles a linear state space model of the form

$$\frac{dx}{dt} = Ax + bu \quad (3.1)$$

$$y = cx + du \quad (3.2)$$

where input u is a power injection at one bus (the site of the brake in this case) and output y is a power flow on a line (the line instrumented during the brake test). This model employed simple machine representation; only two state variables (speed and angle) per machine. A performance function was then defined as the sum of squares of frequency response magnitude errors at a countable set of frequencies. The response magnitude error is the difference of the response provided by BPA and that calculated from the simple linear model, that is,

$$\frac{|Y(j\omega)|}{|U(j\omega)|} = |c(j\omega I - A)^{-1}b + d| \quad (3.3)$$

An iterative process was set up to seek a set of system parameter estimates which would minimize the performance function. This was done

by the method of steepest descent. During the iterative process, the structure of the physically based model was fixed, and only parameters (inertias, reactances, damping factors, etc.) were varied. Two system structures were used in two separate parameter estimation attempts. One structure was a three machine system (Pacific Northwest, Lower Columbia, and San Francisco machines; Los Angeles as an infinite bus). The other structure was a four machine system (machines at all four locations). Initial parameter estimates were obtained from data supplied by BPA.

Of the two structures employed, the three machine configuration was thought to give a better match to the measured response. Fig. 3.3 is a Bode magnitude plot of the small signal frequency response obtained with this model and "optimum" parameters as found by steepest descent minimization. This figure may be compared with Fig. 3.4, which is the frequency response calculated by BPA from the brake test time response. The structure and parameter values for the three machine model are given in Fig. 3.5. The frequency response of Fig. 3.4 displays a well damped resonance at about 0.05 Hz which is not present in the model frequency response of Fig. 3.3. This resonance is thought to be due to regulators which are not included in the simple model.

It is interesting to observe the changes in parameter values from initial estimates which occurred during the iterative process. The rightmost machine in Fig. 3.5 was originally assigned an inertia and reactance representative of the generation in the San Francisco area as given in Fig. 3.2. As the iteration proceeded, the reactance greatly decreased and the inertia increased. This, together with an increase in the reactance of the line from Lower Columbia to the south

seems to indicate that this machine became a Los Angeles area model rather than a San Francisco area model. In other words, the dynamics of the relatively small San Francisco equivalent machine may not be significant to brake test response. It is felt that this is the reason that the four machine structure that was attempted was not as successful as the three machine structure.

3.4 Results of Computer Study

The time response of the AC Intertie power or current is shown in Fig. 3.6. This plot was also shown in Progress Reports C00-4206.4, April 1978 and C00-4206-4, July 1978. The application of the brake is a 1300 MW, 0.5 sec. power pulse. Two coordinates are given in Fig. 3.6. One for the change in AC Intertie power and one for the change in the magnitude of the rms AC Intertie current. This curve was furnished by BPA.

The curve shown in Fig. 3.7 is the magnitude of the AC Intertie power obtained from the computer representation of the three machine physically based equivalent model shown in Fig. 3.5. There is an initial AC Intertie power flow of approximately 1300 MW, however, in Figs. 3.6 and 3.7 the change of power from the steady state value is plotted rather than the total power. Although the time responses shown in Figs. 3.6 and 3.7 are similar the comparison is not markedly improved from that obtained by the trial and error approach (Progress Report C00-4206-5, July 1978). Since in Fig. 3.5 the machines are represented as a voltage behind a reactance the simulation is much reduced from that used in the work reported in C00-4206-5, July 1978.

As reported in Progress Report C00-4206-4, April 1978, the compensator was designed for the IC unit using a transfer function approach to

represent the West Coast power system. The response of the AC Intertie current to a 10MW brake application for 0.5 sec obtained using this approach to design the controller gain is shown Fig. 3.8. Since in the transfer function approach the system is assumed linear this response would be identical in waveform to that for a brake application of 1400 MW.

A representation of the IC unit was incorporated into the BPA equivalent system shown in Fig. 3.5. The response of the AC Intertie power of the three machine equivalent (Fig. 3.5) is shown in Fig. 3.9. Two time responses are shown: one for the brake test without the compensator (a repeat of Fig. 3.7) and one with the compensator in service. The damping of the AC Intertie power appears to correspond to that obtained by the transfer function approach (Fig. 3.8).

3.5 Conclusions

A second method of establishing a physically based model of the West Coast power system has been presented. Although this straight forward approach yields more insight to the system than the trial and error approach reported earlier, the comparison of the time response of the AC Intertie power during the brake test indicates that the model could be improved.

The physically based model was used to verify the compensator design which was determined previously from the transfer function approach. It appears that this compensator design which was developed by BPA will suffice although some changes may be necessary in order to accommodate future system constraints. This concludes Purdue's work on this phase of the contract. Unless otherwise instructed Purdue will not become further involved in the design of the IC unit and associated controls.

Fig. 3.1 BPA equivalent system.

Fig. 3.2 BPA equivalent system studied.

Fig. 3.3 Bode Plot of Small Signal Frequency Response of a Three Machine System.

Fig. 3.4 Bode Plot Calculated from Brake Test Time Response.

Fig. 3.5 Three Machine Equivalent Model of West Coast Power System.

Fig. 3.6 AC intertie response due to 0.5 sec.,
1300 MW energization of Chief Joseph Dynamic Brake.

Fig. 3.7 AC Inertial Power Response During Brake Test-
Three Machine Representation.

Fig. 3.8 Magnitude of AC Intertie current during a 10MW brake test-transfer function approach with IC unit in service.

Fig. 3.9 AC Intertile Power During Brake Test -
Three Machine Equivalent Representation - With and Without Compensator.