SECURITY ASSESSMENT
OF POWER SYSTEMS
INCLUDING ENERGY STORAGE

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ABSTRACT

Energy Storage

Based on system response data provided by the Bonneville Power Administration, it has been confirmed that 10 MW is an adequate capacity for the IC unit which is proposed for supplementary damping of the West Coast intertie, for the degree of damping which BPA considers as adequate. Some preliminary investigations have shown that IC units, with appropriate controls, should be capable of preventing the buildup of torsional oscillations in turbogenerators connected to series compensated transmission lines (subsynchronous resonance).

Identification

The implementation of an adequate 'white noise' generator has allowed confirmation of an analog simulation of a power system with load variations. Autocorrelation estimates of signals measured on this simulation indicate that machine rotor angle dynamics should be readily identifiable, but dynamics due to exciters and governors are probably not identifiable. Likelihood functions (as a weighted sum of squares of residuals produced by a Kalman filter) appear to attain maximum value for the 'true' parameters of the system, but the computational burden of doing dynamic estimation in a point estimation problem is prohibitive. The use of canonical forms for system linearized dynamics is being investigated, with the prospect of formulating point estimation type algorithms.

SECTION 1

ENERGY STORAGE

This section of the report concerns the application of various energy storage technologies as controls to improve power system dynamic performance. The report this quarter concerns design of IC unit controls to increase the damping of oscillations on the West Coast Intertie, and the use of IC units to prevent the buildup of subsynchronous oscillations.

1.1 Introduction - BPA Project

Since the December 1977 Progress Report there have been two meetings regarding the IC unit to be placed in the BPA system. On January 5, 1978 a meeting was held at LASL and at St. Louis on March 16, 1978. P.C. Krause's letters dated January 24, 1978 and March 23, 1978 described the proceedings of these meetings.

During the last four months work has been conducted at BPA, LASL and Purdue in an effort to determine the location and size of the IC unit. A considerable amount of information has been exchanged and numerous discussions have taken place. It is not the purpose to detail all of this information in this report. Instead only the most salient features of the BPA project are discussed. The most important, of course, is the recommendation that a 30 MJ/10 MW IC unit placed at the Chief Joseph Bus should be sufficient to damp the AC Intertie power oscillations.

1.2 Description of System Studied - BPA Project

The system studied using the transfer function approach is shown in block diagram form in Fig. 1.2-1. This system was simulated and studied using the hybrid computer at Purdue.

Fig. 1.2-1 Block diagram of BPA system - transfer function approach.

Information regarding the parameters of the IC unit were obtained from H. Boenig of LASL. It is assumed that the IC unit is connected to a 230 kV Chief Joseph bus with a 12.75 MVA transformer with 1 kV line-to-line voltage on both secondary transformers (12 pulse converter). The inductance (L) is 2.4 h and the maximum inductor current (I_{IC}) is 5000 A. The commutating reactance (X_c) is 0.00784 ohms which is 10% of base impedance.

The transfer function $G(s)$, $H(s)$ and $C(s)$ were furnished by R.L. Cresap and J.F. Hauer of BPA. $G(s)$ is a transfer function obtained for the response of the AC Intertie power to energization of the Chief Joseph Dynamic Brake. In order to obtain a good comparison with an actual system response, it was found by BPA that $G(s)$ is a 15th order transfer function of the following form expressed in AC Intertie MW per brake MW.

<u>Block</u>	<u>Function</u>
1	$\frac{s - 0.08403}{s + 0.2953}$
2	$\frac{.00975(s^2 + 0.672s + 0.7241)}{s^2 + 0.8434s + 0.3173}$
3	$\frac{s^2 + 0.7718s + 10.65}{s^2 + 0.5088s + 4.966}$
4	$\frac{s^2 + 50.96s + 702.43}{s^2 + 0.8900s + 12.87}$
5	$\frac{s^2 + 0.7294s + 16.54}{s^2 + 1.038s + 25.17}$
6	$\frac{s^2 + 2.27s + 33.78}{s^2 + 2.246s + 45.48}$

<u>Block</u>	<u>Function</u>
7	$\frac{s^2 + 0.2678s + 58.85}{s^2 + 3.14s + 56.31}$
8	$\frac{s^2 + 0.911s + 84.25}{s^2 + 1.577s + 83.23}$

The transfer function $H(s)$ provides a means of modeling the power noise recorded on the AC Intertie Monitor. $H(s)$ consists of three blocks in series with a 1 MW white noise source (P_n). The output, P_N , is added to P_{IT}' , the output of $G(s)$, to yield the AC Intertie power, P_{IT} . BPA furnished three sets of data for $H(s)$ corresponding to three different intertie loads; 1680, -140 and 920 MW. The 1680 MW load (export) is the case considered in this study. For this condition $H(s)$ is

<u>Block</u>	<u>Function</u>
1	$\frac{9.887}{s}$
2	$\frac{s^2 + .5476s + 1.138}{s^2 + .3108s + 1.431}$
3	$\frac{s^2 + .9428s + 5.565}{s^2 + .4058s + 5.395}$

The transfer function $C(s)$ is the compensator or controller shown in block diagram form in Fig. 1.2-2. This is similar to that used by BPA on their HVDC modulation control. The parameters are

ω_D	20.0	radians/second	ω_{NP}^2	50.0	(radians/second) ²
ω_{LP}	20.0	radians/second	σ_Z	1.0	seconds ⁻¹
ω_{LD}	1.5	radians/second	σ_P	10.0	seconds ⁻¹
ω_{NZ}^2	50.0	(radians/second) ²			

The design value of K given by BPA is $K = 0.46$.

Fig. 1.2-2 Block diagram of compensator.

1.3 Computer Study - BPA Project

The time response of the AC Intertie power due to the energization of the Chief Joseph Dynamic Brake as predicted by $G(s)$ is shown in Fig. 1.3-1. The application of the brake is approximated by a 1300 MW, 0.5 sec. power pulse.

The compensator gain was determined from a root-locus analysis of the system shown in Fig. 1.2-1 with zero power noise, P_n . Also, since the inductance of the IC unit is large it is possible in this analysis to bypass the IC unit and connect the output of the compensator, (C) directly to the input of $G(s)$. It is understood that $P_{ref} = 0$. A root-locus plot in the range of frequencies of interest is shown in Fig. 1.3-2. From this type of analysis BPA determined that a value for K of 0.46 was an appropriate gain for the compensator. The root-locus plot furnished by BPA was duplicated at Purdue.

The frequency response of the system shown in Fig. 1.2-1 is given in Table 1.3-1. This frequency response analysis was performed with a linearized representation of the converter so that the transfer ratio of $P_{IT}(s)$ to $P_n(s)$ is $H(s)/(1-C(s)G(s))$. Table 1.3-1 lists $H(s)$, $C(s)$, $G(s)$, and $H(s)/(1-C(s)G(s))$ for $s = j\omega$. It is noted that for $\omega = 2.29$ rad/sec. (about 1/3 Hz) the ratio $P_{IT}(s)/P_n(s)$ has an amplitude of 2.24. Thus the control reduces the amplitude of the 1/3 Hz component of AC Intertie power fluctuation by a factor of 2.24. This calculation is verified in Fig. 1.3-3 wherein traces of $P_n(t)$, $P_N(t)$, $P_{IC}(t)$, $P_{IT}(t)$, $P_c(t)$, $V_{IC}(t)$, and $I_{IC}(t)$ are given for $P_n(t)$ a 1/3 Hz sinusoid. In the steady state the amplitude of $P_N(t)$ is approximately 12 MW while the steady state amplitude of $P_{IT}(t)$ is approximately 5 MW, a reduction by a factor of 2.4.

Figures 1.3-4 and 1.3-5 show the system with $P_n(t)$ represented as a "bandwidth limited white noise" with $S(\omega) = 1 \text{ MW}^2\text{-sec}$ for all frequencies ω up to about 6 rad/sec., where

Fig. 1.3-1 AC Intertie power (P_{iT}) due to a 0.5 sec.,
1300 MW energization of Chief Joseph Dynamic Brake.

Fig. 1.3-2 Root-locus plot of system shown in Fig. 1.2-1.

Table 1.3-1 Frequency Response of System
Shown in Fig. 1.2-1.

$\omega(\frac{\text{rad}}{\text{s}})$	$H(j\omega)$		$C(j\omega)$		$G(j\omega)$		$H(j\omega)/1-C(j\omega)G(j\omega)$	
.100	81.081	-87.9	.007	174.6	.573	-79.1	81.067	-87.8
.105	77.426	-87.8	.007	174.3	.585	-81.7	77.419	-87.7
.110	73.936	-87.7	.008	174.1	.598	-84.3	73.937	-87.6
.115	70.603	-87.6	.009	173.8	.612	-87.0	70.612	-87.5
.120	67.419	-87.5	.010	173.5	.626	-89.7	67.439	-87.4
.126	64.378	-87.4	.011	173.2	.640	-92.5	64.410	-87.2
.132	61.474	-87.3	.012	172.9	.655	-95.3	61.520	-87.1
.138	58.701	-87.1	.013	172.5	.670	-98.1	58.762	-86.9
.145	56.052	-87.0	.014	172.2	.686	-101.0	56.130	-86.8
.151	53.522	-86.8	.015	171.8	.702	-103.9	53.620	-86.6
.158	51.105	-86.7	.017	171.4	.718	-106.9	51.225	-86.4
.166	48.797	-86.5	.018	171.0	.734	-109.9	48.941	-86.2
.174	46.592	-86.4	.020	170.6	.750	-112.3	46.764	-86.0
.182	44.486	-86.2	.022	170.2	.766	-116.0	44.687	-85.8
.191	42.475	-86.0	.024	169.7	.782	-119.1	42.708	-85.6
.200	40.553	-85.8	.025	169.2	.798	-122.2	40.821	-85.4
.209	38.718	-85.6	.029	168.7	.813	-125.4	39.023	-85.2
.219	36.965	-85.4	.032	168.2	.827	-128.6	37.309	-84.9
.229	35.290	-85.1	.035	167.6	.841	-131.9	35.676	-84.7
.240	33.690	-84.9	.038	167.1	.853	-135.2	34.120	-84.4
.251	32.162	-84.6	.041	166.5	.865	-138.5	32.636	-84.2
.263	30.702	-84.3	.045	165.8	.875	-141.9	31.222	-83.9
.275	29.308	-84.0	.050	165.2	.883	-145.3	29.873	-83.6
.288	27.975	-83.7	.054	164.5	.889	-148.7	28.586	-83.4
.302	26.702	-83.4	.059	163.8	.894	-152.2	27.357	-83.1
.316	25.486	-83.0	.065	163.0	.895	-155.7	26.182	-82.8
.331	24.324	-82.6	.071	162.2	.895	-159.2	25.058	-82.5
.347	23.215	-82.2	.078	161.4	.891	-162.6	23.980	-82.3
.363	22.154	-81.8	.085	160.6	.885	-166.1	22.946	-82.0
.380	21.141	-81.3	.093	159.7	.875	-169.6	21.951	-81.7
.398	20.174	-80.8	.102	158.7	.862	-173.0	20.994	-81.4
.417	19.250	-80.3	.111	157.8	.846	-176.3	20.071	-81.1
.437	18.368	-79.7	.121	156.8	.826	-179.6	19.180	-80.7
.457	17.525	-79.0	.133	155.7	.803	-177.3	18.320	-80.3
.479	16.722	-78.3	.145	154.6	.777	-174.3	17.490	-79.9
.501	15.956	-77.5	.158	153.5	.748	-171.6	16.691	-79.4
.525	15.226	-76.7	.172	152.3	.717	-169.1	15.922	-78.8
.550	14.531	-75.7	.188	151.1	.685	-166.9	15.186	-78.1
.575	13.872	-74.6	.205	149.8	.651	-165.1	14.484	-77.2
.603	13.247	-73.4	.223	148.4	.618	-163.7	13.819	-76.3
.631	12.659	-72.1	.242	147.1	.584	-162.9	13.194	-75.1
.661	12.108	-70.6	.264	145.6	.553	-162.5	12.613	-73.7
.692	11.599	-68.8	.287	144.1	.524	-162.8	12.081	-72.1
.724	11.135	-66.8	.311	142.6	.498	-163.6	11.604	-70.3
.759	10.726	-64.5	.338	141.0	.477	-165.0	11.193	-68.1
.794	10.387	-61.8	.366	139.3	.460	-166.9	10.862	-65.6
.832	10.138	-58.7	.397	137.6	.449	-169.1	10.635	-62.6
.871	10.015	-55.1	.430	135.9	.443	-171.5	10.549	-59.3
.912	10.072	-51.2	.465	134.0	.442	-174.0	10.663	-55.8
.955	10.395	-47.2	.502	132.2	.447	-176.4	11.070	-52.1

Table 1.3-1 (Continued)

1.000	11.100	-43.6	.542	130.2	.457	178.6	11.900	-49.1
1.047	12.323	-41.6	.585	128.2	.471	-179.6	13.306	-47.7
1.096	14.106	-42.8	.630	126.2	.490	-178.1	15.344	-49.8
1.148	16.070	-48.8	.677	124.1	.512	-177.0	17.604	-56.8
1.202	17.149	-58.9	.727	121.9	.533	-176.4	18.902	-68.2
1.259	16.569	-69.6	.780	119.7	.558	-176.1	18.346	-80.4
1.318	14.961	-77.5	.836	117.4	.602	-176.2	16.591	-90.2
1.380	13.245	-82.0	.895	115.1	.642	-176.6	14.646	-96.9
1.445	11.801	-84.1	.956	112.7	.687	-177.5	12.925	-101.5
1.514	10.672	-84.7	1.019	110.3	.740	-178.8	11.470	-105.0
1.585	9.812	-84.3	1.086	107.8	.803	179.4	10.214	-107.8
1.660	9.174	-83.3	1.154	105.3	.886	177.0	9.085	-110.2
1.738	8.727	-81.8	1.225	102.7	.976	173.7	8.032	-112.0
1.820	8.469	-80.1	1.299	100.0	1.097	169.1	7.036	-113.1
1.905	8.427	-78.4	1.374	97.3	1.253	162.6	6.109	-112.8
1.995	8.671	-77.2	1.450	94.6	1.445	153.0	5.311	-110.3
2.089	9.313	-77.8	1.528	91.8	1.648	138.7	4.767	-105.1
2.188	10.372	-82.9	1.607	88.9	1.747	118.9	4.660	-98.6
2.291	11.072	-95.7	1.686	86.0	1.597	96.8	4.946	-97.3
2.399	9.863	-111.5	1.765	83.0	1.272	78.6	4.915	-102.1
2.512	7.730	-120.2	1.844	79.9	.953	66.4	4.464	-105.2
2.630	6.131	-121.9	1.921	76.8	.706	59.5	4.052	-105.3
2.754	5.118	-120.3	1.995	73.6	.526	56.5	3.758	-104.6
2.884	4.460	-117.8	2.066	70.3	.396	57.1	3.526	-104.1
3.020	4.002	-115.2	2.133	67.0	.306	61.8	3.305	-104.1
3.162	3.659	-112.9	2.193	63.6	.251	70.5	3.075	-104.1
3.311	3.387	-110.8	2.247	60.1	.230	80.3	2.839	-103.5
3.467	3.161	-108.9	2.291	56.5	.229	85.4	2.635	-101.8
3.631	2.967	-107.4	2.324	52.9	.218	85.1	2.507	-99.6
3.802	2.795	-106.0	2.344	49.2	.185	86.9	2.426	-99.1
3.981	2.641	-104.8	2.349	45.4	.156	98.2	2.316	-98.8
4.169	2.501	-103.7	2.336	41.6	.160	116.2	2.154	-100.5
4.365	2.371	-102.8	2.301	37.7	.203	128.1	1.961	-100.3
4.571	2.251	-101.9	2.244	33.8	.276	129.1	1.769	-98.2
4.786	2.140	-101.2	2.161	30.0	.364	119.8	1.615	-99.3
5.012	2.035	-100.5	2.049	26.3	.422	102.2	1.582	-86.4
5.248	1.936	-99.8	1.907	22.9	.406	83.6	1.680	-82.6
5.495	1.843	-99.3	1.734	19.9	.351	70.6	1.771	-83.6
5.754	1.756	-98.7	1.530	17.7	.304	62.4	1.781	-86.4
6.026	1.673	-98.2	1.298	17.0	.273	55.1	1.738	-89.0
6.310	1.594	-97.8	1.047	19.3	.246	45.0	1.60	-91.4
6.607	1.520	-97.4	.802	27.9	.209	30.9	1.579	-93.4
6.918	1.449	-97.0	.632	48.7	.152	14.2	1.478	-94.7
7.244	1.382	-96.6	.662	78.8	.083	-.0	1.388	-95.2
7.586	1.318	-96.3	.913	98.8	.025	19.1	1.312	-95.7
7.943	1.257	-95.9	1.283	106.9	.038	95.3	1.232	-96.4
8.318	1.200	-95.6	1.709	108.6	.061	91.8	1.148	-96.6
8.710	1.145	-95.4	2.167	107.6	.062	82.1	1.078	-95.9
9.120	1.092	-95.1	2.641	105.0	.051	85.4	1.029	-95.7
9.550	1.042	-94.8	3.124	101.5	.055	98.9	.970	-96.3
10.000	.995	-94.6	3.608	97.5	.065	98.2	.902	-96.1

Fig. 1.3-3 Response of system shown in Fig. 1.2-1 to sinusoidal noise input.

Fig. 1.3-4 Response of system shown in Fig. 1.2-1 to bandwidth limited white noise input.

Fig. 1.3-5. Same as Fig. 1.3-4 with expanded time scale.

$$S(\omega) \triangleq \frac{1}{4} \int_{-\infty}^{\infty} R(\tau) e^{-j\omega\tau} d\tau, \quad \omega \geq 0$$

Herein, $R(\tau)$ is the autocorrelation function of $P_n(t)$. The same mode of operation is depicted in both figures. The recording scale is expanded in Fig. 1.3-5 for the purpose of portraying the noise input. In all the studies performed, the output of the compensator P_c did not exceed 10 MW and the converter voltage (V_{IC}) did not exceed 2.5 kV.

1.4 Equivalent System - BPA Project

In Section V of the December 1977 Progress Report the approach to be used to develop a detailed representation of an equivalent of the West Coast system was outlined. At that time, we had requested C.W. Taylor to furnish what he thought would be an appropriate first approximation of the system. This information was received in mid-December 1977 and is given in Fig. 1.4-1. Although a part of this system has been simulated, this phase of the BPA project has not progressed as fast as we had originally anticipated. However, since the sizing of the IC unit is now complete this work has first priority.

As outlined in the December 1977 report, the simulation of the system shown in Fig. 1.4-1 will be completed and will be compared to that obtained from tests. The parameters of the system and specifically of the generator and loads will be determined somewhat by trial and error and from information obtained from power noise measurements. The work of Prof. Triezenberg on parameter identification, which is a part of this contract, and the consultation of R.L. Cresap will be invaluable in determining the system parameters. Once a reasonably accurate equivalent system has been developed, the IC unit designed from the transfer function approach will be simulated. When this is accomplished the following studies may be performed: nonlinear operation of the IC unit, the operation of the IC unit at various loads and operation of the IC unit during large system excursions.

Fig. 1.4-1 West Coast equivalent system.

1.5 Conclusions and Work Schedule - BPA Project

From studies performed by BPA and Purdue, it appears that a 30 MJ/10 MW IC unit is sufficient in size to be used as a backup for the HVDC modulation to damp the AC Intertie oscillations. The sizing of the IC unit has been the primary objective during the last three months of this contract. Now that this has been completed the next several months will be devoted to the development of the equivalent system simulation outlined in Section 1.4.

1.6 Introduction to SSR Studies

One of the original objectives of this contract was to investigate the use of energy storage to improve dynamic and transient stability of power systems. After the April 1977 meeting, it was decided to expand this contract to include the study of the placing of an IC unit (SMES) in the BPA system for backup protection for damping of the AC Intertie power. At that meeting, other uses of IC units to improve dynamic and transient stability of power systems were discussed. One of considerable interest was the possible application of the IC unit to damp or sustain subsynchronous resonance (SSR). This interest was further accelerated due to a recent RFP from EPRI. The following sections summarize the work which has been done thus far using the IC unit to damp SSR.

1.7 Description of System for SSR Studies

The system shown in Fig. 1.7-1 was used to study the application of the IC unit to damp SSR. The system is patterned after the IEEE Benchmark Model [1]. Per unit machine parameters and capacitor values for the modes investigated are as follows:

[1] IEEE Committee, "First Benchmark Model for Computer Simulation of Subsynchronous Resonance," IEEE Trans. on PAS, Vol. 96, September/October 1977, pp. 1565-1572.

Fig. 1.7-1 System studied for SSR.

$$\begin{aligned}
 X_{ad} &= 1.66 & X_{aq} &= 1.66 \\
 r_a &= 0 & X_{ls} &= 0.130 \\
 r_{fd} &= 0.0019 & X_{lfd} &= 0.1064 \\
 r_{kdl} &= 0.0207 & X_{lkdl} &= 0.150 \\
 r_{kql} &= 0.00526 & X_{lkql} &= 0.1045
 \end{aligned}$$

	<u>Mode 1</u>	<u>Mode 3</u>
r_{kd2}	0.0621	0.0440
X_{lkdl}	0.1845	0.0892
r_{kq2}	0.0531	0.0507
X_{lkq2}	0.1142	0.0838
X_c	0.52	0.287

The mechanical system consists of a high, intermediate, and two low pressure turbines. The parameters of the mechanical system are given below. Mechanical damping was not included in the representation.

<u>Mass</u>	<u>Shaft</u>	<u>H(sec)</u>	<u>K(pu Torque/rad)</u>
HP	HP-IP	0.0929	19.3
IP	IP-LPA	0.1556	34.93
LPA	LPA-LPB	0.8587	52.04
LPB	LPB-GEN	0.8842	70.86
GEN	GEN-EXC	0.8685	2.822
EXC		0.0342	

The parameters of the 12.75 MW IC unit are identical to those used in the BPA study. In this study, however, the converter was represented in detail as a 12 pulse converter.

1.8 SSR Computer Studies

The normal buildup of self-excited SSR is shown in Fig. 1.8-1 for Mode 1 and Fig. 1.8-2 for Mode 3. All shaft torques are shown as well as the electromagnetic torque, T_e , the converter voltage, V_{IC} , and phase a voltage of the capacitor, V_{ac} . All variables are in per unit. Initially the system is operating with 1.0 per unit power delivered from the machine. In order to establish this steady state operating condition a large, fictitious damping is represented in the mechanical system. Once the operating condition is achieved, the damping is removed and the torques are allowed to build up due to SSR.

In Figs. 1.8-1 and 1.8-2 the converter is operated slightly in the invert mode with the inductor current held at 4500 amps. The converter was not controlled for the purpose of damping SSR. In a portion of the computer trace the recording time scale is expanded so that the switching of the converter is observable.

Figures 1.8-3 and 1.8-4 are for the same mode of operation as in Figs. 1.8-1 and 1.8-2 respectively with an IC unit damping control incorporated. In Fig. 1.8-3 the damping control was put in service before SSR was allowed to build up. In Fig. 1.8-4 the damping control was put in service after some building up of the torque oscillations due to SSR had occurred. The instant the damping control was put in service is clear from the plot of V_{IC} .

Figure 1.8-5 shows the operation (Mode 1) of the system, without damping control, as a result of a 4.5 cycle, 3-phase fault at the infinite bus end of the transmission line (Fig. 1.7-1). This recording should be compared to Fig. 1.8-6 which shows the response of the system to the same fault but with the IC

Fig. 1.8-1 Normal buildup of SSR - Mode 1.

Fig. 1.8-2 Normal buildup of SSR - Mode 3.

Fig. 1.8-3 Same as Fig. 1.8-1 with damping control on IC unit.

Fig. 1.8-4 Same as Fig. 1.8-2 with damping control on IC unit.

Fig. 1.8-5 Three phase fault cleared after 4.5 cycles,
no damping control - Mode 1.

Fig. 1.8-6 Same as Fig. 1.8-5 with damping control on IC unit.

damping control in service. Although the capacity of the 12.75 MW IC unit is too small to sustain or damp the torque oscillations due to this 3-phase fault, it does slow the rate of buildup of these oscillations.

1.9 Conclusions From SSR Studies

It is clear from the studies that the IC unit can be used to damp or sustain the torque oscillations due to SSR and that this can be accomplished economically since a superconducting inductor is probably not necessary. In the studies presented, the damping control was a simple control which sensed the change of generator electric power and controlled the firing of the converter. There are other variables which might also be considered. For example, shaft speed, capacitor voltage, or side-band current or power. Design of an improved method of control would require considerable analysis beginning with a small displacement model of the system shown in Fig. 1.7-1.

Clearly, the work presented here opens the door to a large investigation involving various types of energy storage devices and the control thereof. However, it appears that this work will not be continued under this contract.

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 Implementation of Noise Generators

Due to the observed inadequacy of the electronic noise generators in the Energy System Simulation Laboratory, the implementation of a digital noise generator was undertaken. The resulting software produces 30 bit random integers, and the upper 15 bits are converted to analog "noise" via D/A converters acting as zero order sample and hold devices. The autocorrelation function of this analog random process is the same as that of discrete interval binary noise (DIBN) with an extremely long repeat time. Analysis of the responses of systems driven by this process shows that the autocorrelation function can be considered to be

$$R(\tau) = R(0) \left(1 - \frac{|\tau|}{T}\right) \quad \text{for } |\tau| < T$$
$$= 0 \quad \text{for } |\tau| > T$$

where T is the sample interval. The power spectrum of such a signal is of nearly constant amplitude for all frequencies below a cutoff that is inversely proportional to T .

2.2 Confirmation of Analog Simulations

With an adequate analog noise source, it was then possible to confirm

the correct operation of an analog simulation of a one machine system, Fig. 1. This simulation, it is now confirmed, produces a power signal (measured on the line) that has the same autocorrelation function as is predicted analytically.

Fig. 1 - One machine system.

Furthermore, although the simulation is quite detailed (six winding Park's equations for the machine) the measured autocorrelation function is, for all practical purposes, predicted by a simple second order machine model. In other words, only the basic electromechanical swing of the machine against the infinite bus is observable from measurements on the line. This indicates that the proper machine model for an identification algorithm is a "classical" model of constant reactance, damping, and inertia. The next section of this report, by illustration of autocorrelation functions, strengthens this point.

The investigators for this project are proceeding under the generalization that for multimachine systems also, the only dynamics that are observable from network measurements are electromechanical swings.

2.3 Influence of Exciters and Governors on Network Time Series Measurements

There is a question regarding the need to represent the dynamics of machine governors and exciters in the system model for identification. Basically, this is a question of identifiability; can information regarding these

dynamics be extracted from available time series measurements? Questions of this type are addressed in the literature on identification.

Before undertaking a detailed analysis of the influence of exciter and governor dynamics, a simulation study was performed on the one machine system previously described. The results of this simulation study are so negative with regard to obtaining governor and exciter information that further effort in this direction will not be made. The question and mathematical treatment of identifiability are still pertinent in this project, but must be directed toward identifiability in terms of number of machines in the system, number of measurement points, and so forth.

In the simulation study, time series measurements of power signals were taken from the one machine system simulation. Various types of governors and exciters were incorporated in the simulation for the several trials. The time series data were differenced once to cancel the effect of the analog integrators that are used to turn the "white noise" into a Brownian Motion that represents load variation. Figures 2, 3, and 4 illustrate autocorrelation estimates of the differenced time series. These autocorrelation estimates are based on time series length of 10,000 to 20,000 samples.

Figure 2 shows real power autocorrelation for various types of machine excitation. The three plots are practically indistinguishable. An identification algorithm, regardless of its sophistication, would be unable to discern the presence of exciter dynamics in this data.

Reactive power autocorrelation is shown in Fig. 3 for various exciters. Although the curves are distinguishable, they are all of such small magnitude that the information content is probably not useful. On the basis of the information in this figure it appears that time series measurements of reactive power cannot contribute to power system identification. [Reactive power is

Fig. 2 - Real power signal autocorrelation at lag k for various exciters. (Signal differenced once).

Constant Excitation —————

AR Exciter - - - - -

HIR Exciter

Power measurement on transmission line.
Sampling interval = 0.1 sec.

Fig. 3 - Reactive power signal autocorrelation at lag k for various exciters. (Signal differenced once).

Constant Excitation _____

AR Exciter - - - - -

HIR Exciter

Power measurement on transmission line.
Sampling interval = 0.1 sec.

Fig. 4 - Real power signal autocorrelation at lag k for various governors. (Signal differenced once).

Constant torque	_____
Hydro governor	-----
Steam governor	

Power measurement at machine terminals.
Sampling interval = 0.1 sec.

herein defined as

$$Q(t) = V_q(t) i_d(t) - V_d(t) i_q(t)$$

where

$$V_q(t) = V_a(t) - \frac{1}{2} V_b(t) - \frac{1}{2} V_c(t)$$

$$V_d(t) = \frac{\sqrt{3}}{2} V_b(t) - \frac{\sqrt{3}}{2} V_c(t)$$

and similar expressions for $i_q(t)$ and $i_d(t)$. The quantities subscripted a, b, and c are actual phase voltages and currents.]

Figure 4 shows the real power autocorrelations for various governor - prime mover combinations. Again, the plots are indistinguishable.

On the basis of the data obtained from this simulation study, it is concluded that there is no reason to include governors or exciters in the system model used by an identification algorithm. Such dynamics would not be identifiable, and would cause the algorithm to fail. Furthermore, it is concluded that the machine model for the identification algorithm had just as well be a simple second order "classical" model. A second order machine model produces power signal autocorrelations that are indistinguishable from those produced by the detailed machine model used in these simulations.

2.4 Likelihood Functions

Some time has been spent in the simulation laboratory in calculating likelihood functions for estimates of the parameters of the one machine system, in the manner described by Schweppe (Uncertain Dynamic Systems, Prentice-Hall, 1973). The Kalman Filter part of this algorithm is based on the classical 2nd order machine model, but the simulation model is, of course, more detailed. It appears that the likelihood function is indeed a maximum when the parameter estimate is accurate (i.e., the machine reactance, damping, and inertia pro-

duce an electromechanical oscillation of the correct characteristics). However, the calculation burden, even for this simple system, is quite oppressive.

Some other recent developments on the project, to be related in the next section of this report, indicate that it may be possible to formulate identification algorithms that do not require Kalman Filter processing.

2.5 Dynamic Equations for Multimachine Systems

The effort was undertaken to write and code an algorithm which assembles equations for the linearized response of a multimachine system to load variations, using a two state variable model for each machine. These FORTRAN subroutines take basic network and machine data, do a load flow, and then perform the matrix manipulations necessary to establish the linearized, small displacement equations. These routines are a necessary utility package for any identification algorithm. As these routines became operational, it was realized that the final state space equations have a very simple and orderly form. (In retrospect, this form now seems very obvious.) The form is illustrated in Fig. 5 for a system with n machines and m measurements points. In this matrix state space equation, W is a scalar white noise input and state variable x_{2n+1} represents the variation of all loads. All other odd numbered state variables are machine angles, and all even numbered state variables are machine speeds, normalized to synchronous speed. Outputs y are power signals measured on various transmission lines. There are $n(n+m+3)$ parameters to be identified, if no prior knowledge is available.

From the structure of these linearized equations, it may be possible to determine the number of outputs, m , that is needed for identification. Also, contrary to previous opinions held by the principle investigator, it may be

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \vdots \\ \dot{X}_{2n-1} \\ \dot{X}_{2n} \\ \dot{X}_{2n+1} \end{bmatrix} = \begin{bmatrix} 0 & \omega_2 & & & 0 & 0 & 0 \\ \alpha_{11} & \beta_1 & & & \alpha_{1n} & 0 & \gamma_1 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & & & 0 & \omega_2 & 0 \\ \alpha_{n1} & 0 & & & \alpha_{nn} & \beta_n & \gamma_n \\ 0 & 0 & & & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{2n-1} \\ X_{2n} \\ X_{2n+1} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ 1 \end{bmatrix} W$$

$$\begin{bmatrix} Y_1 \\ \vdots \\ Y_m \end{bmatrix} = \begin{bmatrix} \delta_{11} & 0 & & & \delta_{1n} & 0 & \epsilon_1 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ \delta_{m1} & 0 & & & \delta_{mn} & 0 & \epsilon_m \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{2n-1} \\ X_{2n} \\ X_{2n+1} \end{bmatrix}$$

Fig. 5 - Form of the linearized equations for an n machine system with m outputs.

possible to implement point estimation type algorithms (e.g. least squares or stochastic approximation) thereby finding coefficients $\alpha, \beta, \gamma, \delta$, and ϵ (Figure 5) directly, and then fitting a network to these coefficients as a second step. This could be a much smaller computational burden than the schemes previously contemplated, which use dynamic estimation to make explicit evaluations of criterion functions.