JUN 23 1961

APAE MEMO NO. 290

AEC Research and
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UC-81, Reactors - Power
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TASK XII ANALYTICAL REPORT
SM-1 TRANSIENT ANALYSIS
BY
ANALOG COMPUTOR METHODS

ALCO PRODUCTS, INC.

NUCLEAR POWER ENGINEERING DEPARTMENT
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**TASK XII ANALYTICAL REPORT
SM-1 TRANSIENT ANALYSIS
BY ANALOG COMPUTER METHODS**

By
J. A. Barrett

Approved By: H. L. Hoover, Project Engineer

Issued: May 26, 1961

Contract No. AT(30-3)-326
with U. S. Atomic Energy Commission
New York Operations Office

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ABSTRACT

The voltage and frequency response of selected SM-1 plant system parameters to step load changes was analyzed using analog computer measurements. The analog model was that developed for analysis of the SM-2 design, previously reported in APAE No. 53. The approach to the analysis, formulation of the model, and analog recordings are presented. The data will be used to prove reliability of the analog model by comparing analog data with test data to be taken at SM-1 as part of Task XII.

ACKNOWLEDGEMENT

The author wishes to acknowledge the assistance and advice provided by the following individuals.

F. S. Rothe, General Electric Corporation, Schenectady, N. Y., for Generator and Exciter System equations and parameter values.

K. Folgate, Data Processing and Statistical Services Branch, The Engineer Research and Development Laboratory, U. S. Army, Fort Belvoir, Virginia, for technical assistance and advice in using the analog computer facility on which the test runs were made.

F. L. Robertson and E. Duffy, who provided administrative supervision and use of the computing facility.

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1.0 SUMMARY

The voltage and frequency response of selected SM-1 plant system parameters to step changes in load was measured using an analog computer. The analog model used and assumptions for the analysis are similar to the model and assumptions for the SM-2 plant transient analysis, reported in APAE No. 53. Results of the analysis will be compared with experimental data to be taken in plant response tests at SM-1 (Task XII). Experimental results will determine accuracy of the SM-2 model parameters and the analytical procedures and assumptions used.

The general approach to the analysis and the formulation of the analog model for the SM-1 tests are discussed. The analog recordings are presented in the Appendix. The conditions for each set of runs, identified by time of the run, are listed. Analog results are tabulated showing the approximate peak values (percent change) for each of the variables under the various conditions imposed. The results show no excessive excursions in plant output voltage and frequency will be present when the SM-1 plant is connected to the load bank, with plant instrumentation and control supplied by the Vepco source.

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2.0. INTRODUCTION

The purpose of this report is to predict the voltage and frequency response to step load changes of the SM-1 nuclear power plant, using the analog model developed for analysis of the SM-2 design (APAE No. 53*). The SM-2 analog model is considered to accurately represent a power plant of the SM-1 type.

The ultimate goal of the data so developed is to prove reliability of this analog model by comparing analog data with test data from Task XII tests. Specifically, the comparison will determine whether:

1. The analytical procedures are correct.
2. Closer approximations should be assigned for some of the questionable parameters, such as actuator time constant, damping transformer gain, turbine time constant, steam chest time constant, etc.
3. The analysis of the SM-2 plant was carried out on the basis of accurate assumptions.

Some of the assumptions made in this and the SM-2 analysis follow:

1. The turbine is a single time lag system responding in a linear manner to load changes up to 30%.
2. The steam chest can also be treated as a single lag linear system. Further, some verification of the actual value of the steam chest delay is sought.
3. Generator armature resistance is zero. Other assumptions are made with respect to the generator and appear in Section 4.2, dealing with the generator analysis.
4. The steam pipe response to area changes in the turbine speed regulating valve is so fast its effects can be ignored and the steam pipe volume can be considered as part of the steam generator volume. The turbine is considered to be located immediately adjacent to the steam generator with no pipe between the two.
5. The turbine speed control system is a single time lag device with a specified gain producing 4% droop.

* Barrett, J. A., "SM-2 Transient Voltage and Frequency Analysis by Plant Analog Simulation, APAE No. 53, Vol. 1 and 2, November 16, 1959.

A detailed analysis of the SM-1 primary system has been performed in AP Note 262. * This analysis and the previous analysis performed on the SM-2 primary system design (APAE No. 53) show the primary system will have a negligible effect on the voltage and frequency response during the first 2 or 3 seconds of a load impedance change. This is because the primary system power output does not change for several seconds following a load transient.

The SM-2 analysis also shows the feedwater system will have a negligible effect on voltage and frequency response during the first 2 or 3 seconds. For this reason the feedwater system is not included in this analysis.

* Birken, S. H., "Analog Computer Analysis for the Proposed Test XII Measurements," AP Note 262, Alco Products, Inc., August 17, 1960.

3.0 APPROACH

An analog model, similar to the one used for the SM-2 transient analysis, (APAE No. 53) has been developed to simulate the SM-1 plant response to electrical load impedance changes. This model includes representation of the generator, exciter, turbine, and electrical load. It does not include the primary system, steam generator, or feedwater system.

A number of analog runs were made with this model on January 27, 1961 at the ERDL Analog Facility located in the Data Process and Statistical Service Branch of the U. S. Army, Fort Belvoir, Virginia.

The following plant parameters are varied in the runs to evaluate their effect on the system response:

1. Power factor (1.0 and .8)
2. Voltage control system
 - a. Exciter field resistance
 - b. Part load performance
 - c. Gain
 - d. Damping
3. Turbine and Speed Control System
 - a. Gain
 - b. Speed control time constant
 - c. Turbine time constant
 - d. Steam chest time constant

The runs are numbered with the time at which they were run. A table showing run number and the particular effect investigated follows.

TABLE 1
ANALOG RUNS - INVESTIGATED EFFECTS

<u>Run No.</u>	<u>Investigated Effect</u>
1030-1111	Nominal system at 0.8 and 1.0 pf; part load operation; exciter shunt field resistance is zero.
1129-1143	Exciter gain
1200-1205	Damping transformer gain
113-156	Turbine speed control gain
157-209	Steam chest time constant
212-214	Turbine time constant
216-218	Effect of actuator time constant on turbine speed control

The nominal parameter values are shown in Appendix 6. 2.

The following parameters are read out in the analog runs:

1. Load current
2. Generator terminal voltage error
3. Diactor controlled resistance
4. Generator terminal electrical power
5. Turbine speed error
6. Direct axis current

The analog runs are shown in Appendix 6. 8.

By comparing the analog results with the actual test runs of Task XII, meaningful conclusions can be drawn about the accuracy of the developed analog model in representing an actual system. Deviations between the analog results and the test results can be identified and improvements can be introduced in the analog model for better representation of the actual system.

4.0 ANALOG MODEL

4.1 GENERAL

The analog program for the complete system is shown in Fig. 1, Appendix 6. 4.

Some function generators have been used to provide non-linear input. Function generators B3X and B2Y (Fig. 7 and 8) extract square roots; D3X and D2Y (Fig. 6 and 9) provide the saturation effects of generator and exciter, respectively.

All nomenclature and equations for the analog circuit are shown in Appendixes 6. 3 and 6. 4 respectively. Next to the equations in the Appendix, the number of the amplifier solving the equation is indicated. The potentiometer settings and the SM-1 plant constants are shown in Appendix 6. 7.

The parameters recorded in the analog runs are shown on a per unit basis. By comparing the analog volts with the volts per unit the percentage change of the parameter during the transient can be read from the charts.

4.2 GENERATOR AND LOAD

4.2.1 Generator

The electrical generator at SM-1 is a salient pole machine. The analysis performed on the SM-2 design was done for a round or cylindrical rotor machine. The principal difference is that there is no Potier reactance considered in the salient pole machine analysis. Saturation is a function of terminal voltage rather than Potier voltages. The generator no load saturation curve is shown in Figure 2, Appendix 6. 5.

The armature mmf is assumed to be divided into two components, one along the direct axis and the other along the quadrature axis. The armature currents are also represented by vector components along the direct and quadrature axis. The vector diagram is shown in Figure 5, Appendix 6. 5.

The following assumptions have been made.

1. Subtransient effects are neglected.
2. Armature resistance is negligible.
3. Speed of armature rotor does not affect the generator terminal voltage. This is not strictly true for a droop type control, but is considered negligible for the 1. 5% (or less) speed changes obtained from 30% load changes.

4. Load power factor is constant.
5. Transmission line effects from generator and load are neglected.

The generator field and terminal voltage equations are given in Appendix 6. 4.

4. 2. 2 Load

The load impedance is presented as the vectorial sum of load resistance and reactance. A relationship results showing armature current in terms of generator terminal voltage and load impedance. These relationships are derived in Appendix 6. 4.

The quadrature and direct axis components of current and voltage are considered equal at the generator terminals and the load terminals.

In the representation used in this analysis, one per unit load impedance is Z^2 for both unit and 0. 8 power factor conditions. This enables setting the potentiometers to the sine and cosine values directly. It has the disadvantage of providing different one per unit values for the direct axis and quadrature axis components of the armature current for the 0. 8 and 1. 0 power factor conditions.

4. 2. 3 Exciter

The exciter output is a function of exciter terminal voltage, the saturation effect of the exciter field and exciter field circuit resistance. The exciter equations are given in Appendix 6. 4. It was found that where approximately 14 ohms is necessary for control, total capability of the controllable resistance is 5900 ohms in the exciter field circuit. The exciter saturation curve is shown in Fig. 3. Figure 4 shows controlled resistance vs. voltage error.

4. 3 TURBINE

4. 3. 1 Rotor Inertia

The turbine is treated as a single rotor with a polar moment equivalent to the sum of the polar moments of the turbine rotor, gears and generator rotor (reflected through the gears). Losses are considered negligible. The equations describing turbine transient response are given in Appendix 6. 4.

A torque equilibrium equation can be written for the "single rotor." On one end of the rotor a torque is caused by the steam flow in the turbine; on the other end the torque is caused by the electrical load on the generator. If the two torques do not sum to zero, speed change of the rotor will result.

By multiplying either torque by the rotational speed, power is obtained. A change of net power will result in a change in rotor speed.

An expression is derived showing this change in rotor speed as a function of change in shaft power. This expression is a simple lag system. The time constant is called the turbine time constant and contains the inertia characteristic of the rotor. For the SM-1 analysis a turbine time constant of 8 sec is used.

4.3.2 Turbine Speed Control System

The time constant of the hydraulic servo system, which positions the turbine steam admission valves, has been estimated at 0.2 sec. The steam flow through the steam admission valves is considered to be a linear function of the valve position, and steam pressure is assumed constant.

Actually, steam pressure delivered by the steam generator varies with load. In steady state this has the effect of changing the steady state control system gain. During a transient the steam pressure has been shown by previous analysis to vary a negligible amount during the first 2 or 3 sec of the speed transient. Since this is the time interval of interest, in this analysis the steam pressure is assumed constant. Instrumentation at SM-1 will enable an evaluation of this assumption as well as enable values to be obtained for a different model if necessary.

The transfer function for the speed control system relates valve area and the shaft speed error by a simple lag with a time constant of 0.2 sec and a gain of 12 to 50 (varied in the analog runs between these two values). The nominal value used is $K = 25$ (4% droop system). Amplifier 21 represents the speed control system. The gain K is provided at the input of amplifier 23 (rotor inertia).

To obtain steam flow from the steam admission valve area, the area is multiplied by the steam pressure (constant). Simulation of the steam pipe and primary system can be provided at this point if the tests show this to be necessary.

4.3.3 Turbine Steam Chest

The turbine shaft torque response to steam flow change is not immediate. There is a charging time associated with the steam chest void, which causes a time lag to exist between opening the steam admission valve and steam torque applied to the turbine shaft. Although this effect is distributed, an effective time constant, representing the effect of the distributed volumes to be charged, can be used. The turbine manufacturer states this effective time lag to be in the order of 0.003 sec. The effect of different values is investigated up to 0.05 sec.

The transfer function expressing the steam chest effect relates turbine shaft torque and steam flow, and represents a simple lag system with a nominal time constant of 0.003 sec.

5.0 RESULTS

The analog computer recordings are shown in Appendix 6.8. The conditions for each run and the peak values, taken from the recordings, are tabulated together in Table 2 to make comparison of the runs easier. Table 2 shows the maximum deviation and time of occurrence.

The following trends can be observed from the analog runs:

1. Load Level

Steady state turbine speed error increases with decreasing electrical load level. This is expected in an isolated system with droop type control.

2. Power Factor

Power factor has negligible effect on speed error.

Transient voltage error increases with decreasing power factor.

3. Exciter Gain

Exciter gain has no effect on speed error.

4. Damping Transformer Gain

Damping transformer gain has no effect on speed error.

Transient voltage error depends on damping transformer gain.

5. Speed Control System Gain

Steady state speed error increases with lower gain.

No change in transient voltage error due to change in speed control gain.

6. Steam Chest Time Constant

Larger time constant increases transient speed error and causes less damped response.

No change in voltage error due to change in steam chest time constant.

7. Turbine Time Constant

Larger time constant decreases transient speed error.

No change in voltage error due to change in turbine time constant.

8. Actuator Time Constant.

Larger actuator time constant increases transient speed error.

No change in voltage error due to change in actuator time constant.

The analog results indicate that no excessive excursions in plant output voltage and frequency will be present when the plant system output is connected to the load bank, with plant instrumentation and control supplied by the Vepco source. Maximum generator terminal voltage expected is 5000 volts and maximum turbine speed deviation of 6% is possible.

TABLE 2
APPROXIMATE PEAK VALUES (% CHANGE) OF TRANSIENTS

Run. No.	Load Current		Generator Term Voltage Error		Gen. Term Electr. Power		Turbine Speed Error		Direct Axis Current	
	%	Sec	%	Sec	%	Sec	%	Sec	%	Sec
NOMINAL CONDITIONS										
1030	Nominal conditions; 0.8 P. F.; 85% load level									
	+25	2	-6.25	2	+28	2	-1.8	1	+56	2
	-25	Step	-4.36	2	-19	2	+1.25	2	-45	1
1039	P.F. = 1; Nom. Conditions except exciter shunt field resistance = 0; 85% load level									
	+25	Step	+1.25	0.3	+25	Step	-1.6	1	+45	Step
	-25	Step	-3.1	1	-25	Step	+1.25	.8	-45	Step
1053	Nominal conditions; P. F. = 1; 55% load level									
	+25	Step	+ .6	0.5	+19	Step	-1.1	1	+28	Step
	-25	Step	-3.43	1	-19	Step	+ .94	.8	-28	Step
1057	Same as 1053; P. F. = .8									
	+25	1	-4.6	1.3	+25	1	-1.25	1	+45	1
	-25	Step	-3.8	.8	-19	Step	+ .93	.8	-45	Step
1103	Nominal conditions; P. F. = .8; 25% load level									
	+30	Step	-11.55	2.0	+30	Step	-1.87	1	+56	Step
	-30	Step	- 6.2	.9	-28	Step	+1.40	.8	-56	Step
EFFECT OF EXCITER GAIN										
1129	Nominal conditions except exciter gain = 50; P. F. = 1; 85% load level									
	+25	Step	+ .6	.8	+22	Step	-1.4	1	+45	Step
	-25	Step	-1.9	1.2	-22	Step	+1.25	.8	-45	Step
1133	Nominal Conditions; exciter gain = 50; P. F. = .8; 85% load level									
	+25	1	+1.2	1.3	+25	.8	-1.4	1	+45	.8
	-25	Step	-2.4	.8	-22	2	+1.25	2.5	-45	2.0
1139	Nominal conditions except exciter gain = 200; P. F. = .8; 85% load level									
	+30	2	-	-	+30	2	-1.7	1	+56	2
	-25	Step	-10	.7	-19	1.7	+1.1	2	-45	1.8
1140	Same condition as 1139; recorder channel 2 (voltage error) has 10X scale factor									
	+30	2	-21	2	+30	2	-1.7	1	+56	2
	-25	1.8	-12	1	-19	2	+1.1	2.2	-45	2

TABLE 2 (CONT'D)

Run No.	Load Current		Generator Term Voltage Error		Gen. Term Electr. Power		Turbine Speed Error		Direct Axis Current	
	%	Sec	%	Sec	%	Sec	%	Sec	%	Sec
1143	Nominal conditions; exciter gain = 200; P.F.=1; 85% load level									
	+25	Step	+1.2	1	+22	Step	-1.4	1	+45	Step
	-25	Step	-15	1.7	-22	Step	+1.25	.8	-45	Step
EFFECT OF DAMPING TRANSFORMER GAIN										
1201	Exciter System gain =200; P.F.=1; 85% load level; damping transformer gpm=.04									
	+25	Step	+1.9	.5	+22	Step	-1.4	.7	+40	Step
	-25	Step	-13.4	1.6	-22	Step	+1.1	.6	-40	Step
1203	Same as 1201 except damping transformer gain = .08									
	+25	Step	-2.4	.5	+23.5	Step	-1.4	.7	+45	Step
	-25	Step	-15	2.0	-23.5	Step	+1.1	.6	-45	Step
1205	Same as 1201 except damping transformer gain = .01									
	+25	Step	-3.7	1	+25	Step	-1.4	.7	+40	Step
	-25	Step	-15	1.3	-22	Step	-1.25	.6	-40	Step
EFFECT OF SPEED CONTROL SYSTEM GAIN										
113	Nominal Settings except speed control system gain =25; 85% load level									
	+25	Step	-1.6	.5	+25	Step	-1.9	.6	+45	Step
	-25	Step	-5.0	1.2	-25	Step	+1.9	.7	-45	Step
150	Same as 113 except speed control system gain = 50									
	+25	Step	+1.2	.6	+25	Step	- .9	.6	+40	Step
	-25	Step	-5.0	1.2	-25	Step	+ .9	.5	-40	Step
154	Same as 113 except speed control system gain = 50									
	+25	Step	+1.2	.6	+25	Step	- .9	.6	+40	Step
	-25	Step	-5.0	1.2	-25	Step	+ .9	.5	-40	Step
156	Same as 113 except speed control system gain = 12.5									
	+25	Step	+1.2	.5	+25	Step	-2.5	1.3	+40	Step
	-25	Step	-5.0	1.2	-25	Step	+2.5	3.0	-40	Step

TABLE 2 (CONT'D)

Run No.	Load Current		Generator Term Voltage Error		Gen. Term Electr. Power		Turbine Speed Error		Direct Axis Current	
	%	Sec	%	Sec	%	Sec	%	Sec	%	Sec
EFFECT OF STEAM CHEST TIME CONSTANT										
157	P. F. = 1; 85% load level; actuator time constant = .1; steam chest time constant = .1									
	+25	Step	+1.2	.6	+25	Step	-1.25	.6	+40	Step
	-25	Step	-5.0	1.2	-25	Step	+1.25	.5	-40	Step
204	Same as 157 except steam chest time constant = .03; actuator time constant = 0.2									
	+25	Step	+1.2	.6	+25	Step	-1.25	.8	+40	Step
	-25	Step	-5.0	1.2	-25	Step	+1.25	.7	-40	Step
206	Same as 204 except steam chest time constant = .06									
	+25	Step	+1.2	.6	+25	Step	-1.25	.8	+40	Step
	-25	Step	-5.0	1.2	-25	Step	+1.25	.7	-40	Step
208	Same as 206 except steam chest time constant = .2									
	+25	Step	+1.2	.6	+25	Step	-1.7	1.0	+40	Step
	-25	Step	-5.0	1.2	-25	Step	+1.6	.8	-40	Step
209	Same as 206 except steam chest time constant = .5									
	+25	Step	+1.2	.5	+25	Step	-2.2	1.1	+40	Step
	-25	Step	-5.0	1.2	-25	Step	+1.7	.9	-40	Step
EFFECT OF TURBINE TIME CONSTANT										
212	Turbine time constant = 4; P. F. = 1; 85% load level									
	+25	Step	+1.2	.6	+25	Step	-1.6	.5	+40	Step
	-25	Step	-5.0	1.2	-25	Step	+1.6	.4	-40	Step
214	Same as 212 except turbine time constant = 16									
	+25	Step	+1.2	.4	+25	Step	-1.1	1.5	+40	Step
	-25	Step	-5.0	1.2	-25	Step	+1.1	3.0	-40	Step
SPEED CONTROL AND ACTUATOR TIME CONSTANT										
216	Steam chest time constant = .03; turbine time constant = 8; actuator time constant = .1									
	+25	Step	+1.2	.6	+25	Step	-1.25	1.0	+40	Step
	-25	Step	-5.0	1.2	-25	Step	+1.1	3.0	-40	Step
218	Same as 216 except actuator time constant = .4									
	+25	Step	+1.2	.6	+25	Step	-1.6	1.0	+40	Step
	-25	Step	-5.0	1.2	-25	Step	+1.25	.8	-40	Step
220	Zero input voltage position check on recorder.									

6.0 APPENDIXES

6.1 CONDITIONS FOR ANALOG RUNS

Runs 1030 to 1112: Check effects of Part Load Operation and Exciter Shunt Field Resistance.

Run 1030 Nominal conditions; P. F. = 0.8; load swings 100% to 70% and back; chart speed 1 mm/sec.

Run 1032 Same condition as Run 1030; chart speed 5 mm/sec.

Run 1039 P. F. = 1. Nominal conditions except exciter shunt field resistance set equal to zero; load swings 100% to 70% and back.

Run 1053 Nominal conditions; P. F. = 1; load swings 40% to 70% and back.

Run 1057 Same conditions as Run 1053; P. F. = 0.8.

Run 1103 Nominal conditions, P. F. = 0.8; load swings 10% to 40% and back.

Run 1107 Nominal conditions; P. F. = 1; load swings 10% to 40% and back.

Run 1108 Nominal conditions except exciter shunt field resistance set equal to zero; P. F. = 1; load swings 10% to 40% and back.

Run 1111 Nominal conditions except exciter shunt field resistance set equal to zero; P. F. = 0.8; load swings 10% to 40% and back.

Run 1112 Zero recorder input voltage to show zero position of the traces. All traces are increasing in the down direction.

Runs 1129 to 1143: Check effects of Exciter System Gain

Run 1129 Nominal conditions except exciter system gain = 50; P. F. = 1; load swings 70-100% and back.

Run 1133 Nominal conditions except exciter system gain = 50; P. F. = 0.8; load swings 70-100% and back.

Run 1139 Nominal conditions except exciter gain = 200; P. F. = 0.8; load swings 70-100% and back.

Run 1140 Same conditions as Run 1139; Recorder Channel 2, which shows the voltage error, has a scale factor of 10 x the value used in run 1139 to show the full transient voltage swing.

Run 1143 Nominal conditions except exciter gain = 200; P. F. = 1.0; load swings 70-100% and back.

- Runs 1200 to 1205: Check effects of Damping Transformer with Exciter System Gain at 200. The exciter system gain set at 200 enables quicker evaluation of the damping transformer effects as the higher gain system responds in a more underdamped manner. All runs made at P. F. = 1; load change of 70 to 100% and back.
- Run 1200 is a repeat of 1143. Nominal gain of damping transformer is .02.
 - Run 1201 Damping transformer gain = 0.04.
 - Run 1203 Damping transformer gain = 0.08.
 - Run 1205 Damping transformer gain = .01.
- Runs 113 to 156: Check effects of Turbine Speed Control System Gain. All runs are 70-100% and back; nominal settings on all runs except for control system gain.
- Run 113 Speed control system gain = 25. (Nominal control system gain is 25).
 - Run 150 Speed control system gain = 50 (2% droop).
 - Run 154 Speed control system gain = 50 (2% droop).
 - Run 156 Speed control system gain = 12.5 (8% droop).
- Runs 157 to 209: Check Steam Chest Time Constant Effects. All runs at P. F. = 1; 70-100% load swings and back.
- Run 157 Actuator time constant 0.1 sec and steam chest time constant 0.1 sec. It was not planned to run all the tests with these settings; but these values have been designated as the nominal values in order to avoid the necessity of rerunning the previous tests.
 - Run 204 Steam chest time constant 0.03 sec (10 x stated value by manufacturer) and actuator time constant 0.2 sec. Remaining runs made at actuator time constant of 0.2 sec.
 - Run 206 Steam chest time constant 0.06 sec.
 - Run 208 Steam chest time constant 0.2 sec.
 - Run 209 Steam chest time constant 0.5 sec.

Runs 212 and 214: Show effects of Different Turbine Time Constants. Both runs are made at P.F. = 1; load swings are 70-100% and back.

Run 212 Turbine time constant = 4 sec.

Run 214 Turbine time constant = 16 sec.

Runs 216 and 218: Show effect of Speed Control of Actuator Time Constant. Steam chest time constant is 0.03 sec and turbine time constant is 8 sec.

Run 216 Speed control actuator time constant is 0.1 sec.

Run 218 Speed control actuator time constant is 0.4 sec.

Run 220 Checks zero input voltage position on the recorders.

6.2 NOMINAL SYSTEM PARAMETER VALUES

TABLE 3

<u>Description</u>	<u>Unit</u>	<u>Value</u>
Exciter		
Exciter Field Resistance	Ohms	14.1
Exciter System Gain		100 (200)
Damping transformer gain		0.02
Slope no load exciter curve (M)	v/amp	36.6
Unsaturated inductance exciter field	henrys	30.6
Controllable exciter field resistance	ohms	0-5900
Turbine Speed Control		
Gain (4% droop)		25
Speed control time constant	sec	0.1
Steam chest time constant	sec	0.003
Turbine and Generator Rotor		
WR ² turbine	lb/ft ²	1114
WR ² gears (reflected to turbine shaft)	lb/ft ²	148
WR ² generator rotor (refl. to turb. shaft)	lb/ft ²	344
WR ² complete rotor + gears	lb/ft ²	1606
Turbine shaft rated torque	ft-lb	3570
Turbine shaft rated speed	rpm	5489
Turbine time constant including gears and generator rotor	sec	8
Generator		
Direct axis synchronous reactance	per unit ohm	1.42
Direct axis transient reactance	per unit ohm	0.25
Direct axis open circuit time constant	sec	4.3
Quadrature axis synchronous reactance	per unit ohm	0.65
Quadrature axis transient reactance	per unit ohm	0.65
Generator rated shaft speed	rpm	1200

6.3 NOMENCLATURE

Generator

I_a	Current in line a
E_a	Voltage of phase a
I_{aq}	Quadrature axis component of armature current
I_{ad}	Direct axis components of armature current
E_{aq}	Quadrature axis component of armature voltage
E_{ad}	Direct axis component of armature voltage
E_{iq}	Quadrature axis component of synchronous internal voltage
X_d	Direct axis synchronous reactance
X'_d	Direct axis transient reactance
X	Quadrature axis synchronous reactance
X'_g	Quadrature axis transient reactance
T'_{do}	Direct axis open circuit time constant

Load

R_L	load resistance
X_L	load reactance
θ	angle between vectors of R and X
Z	load impedance

Exciter

M	slope of no load exciter saturation curve
L_e	unsaturated inductance exciter field
E_x	exciter terminal voltage
R_e	exciter field resistance
R_x	controllable resistance in the exciter field circuit (0-5900 ohms)

* (In accordance with ASA C 42.10 1957)

S_e exciter field saturation factor

V_D damping transformer voltage output

Turbine

D slope of torque - speed curve

J polar moment of inertia of turbine, gears and generator rotor

L torque on turbine shaft

L_e torque on turbine shaft caused by steam flow

L_s torque on turbine shaft caused by generator rotor load

P_e electrical power

P_s steam power

S operator d/dt

W rotational speed

Speed Control System

A steam admission valve area

K control system gain

W turbine speed

W_R turbine speed set point

Steam Chest

P_s steam power

W_s steam flow

SUBJECT TASK XII
EQUATIONS FOR ANALOG MODEL

GENERATOR

FIELD CIRCUIT:

$$\tau'_{do} \left(\frac{dE_{iq}}{dt} \right) = E_x - X_{ad} I_{ad} \quad (1)$$

$$X_{ad} I_{ad} = E_{iq} + (X_d - X'_d) I_d + S_f \quad (2)$$

S_f IS A FUNCTION OF E_{iq}

$$E_{iq} = \int \left(\frac{dE_{iq}}{dt} \right) dt \quad (3)$$

$$\tau'_{do} \frac{dE_{iq}}{dt} = E_x - [E_{iq} + (X_d - X'_d) I_d + S_f] \quad (4)$$

USING OPERATOR $S = \frac{d}{dt}$

$$[\tau'_{do}] S E_{iq} = E_x - E_{iq} - [X_d - X'_d] I_d - S_f \quad (5)$$

OR $E_{iq} = [E_x - (X_d - X'_d) I_d - S_f] \left[\frac{1}{\tau'_{do} S + 1} \right] \quad (6) \quad \underline{\text{AMP. 19'}}$

TERMINAL VOLTAGE

$$E_{aq} = E_{iq} - X'_d I_{ad} \quad (7) \quad \underline{\text{AMP. 12}}$$

$$E_{ad} = X'_q I_{aq} \quad (8)$$

$$[E_{ad}]^2 = [X'_q I_{aq}]^2 = [X'_q]^2 [I_{aq}]^2 \quad (9)$$

$$E_a = [(E_{aq})^2 + (E_{ad})^2]^{1/2} \quad (10) \quad \underline{\text{AMP. 14.516}}$$

FUNCTION GEN
B3X

LOAD

$$E_a / I_a = R_L + j X_L = \text{LOAD IMPEDANCE} \quad (11)$$

$$\begin{aligned} E_{aq} - j E_{ad} &= [R_L + j X_L] [I_{aq} - j I_{ad}] = \\ &= R_L I_{aq} + X_L I_{ad} + j X_L I_{aq} - j R_L I_{ad} \quad (12) \end{aligned}$$

SUBJECT TASK XII
EQUATIONS FOR ANALOG MODEL

$$E_{aq} = R_L I_{aq} + X_L I_{ad} \quad (13)$$

$$E_{ad} = X_L I_{aq} + R_L I_{ad} \quad (14)$$

$$I_{aq} = \frac{R}{R^2 + X^2} E_{aq} - \frac{X}{R^2 + X^2} E_{ad} \quad (15)$$

$$I_{ad} = \frac{R}{R^2 + X^2} E_{ad} + \frac{X}{R^2 + X^2} E_{aq} \quad (16)$$

USING THE ANGLE Θ BETWEEN VECTORS R & X AND THE VECTOR MAGNITUDE OF IMPEDANCE Z

$$I_{aq} = \frac{\cos \Theta}{Z^2} E_{aq} - \frac{\sin \Theta}{Z^2} E_{ad} \quad (17) \text{ AMP. 10}$$

$$I_{ad} = \frac{\cos \Theta}{Z^2} E_{ad} + \frac{\sin \Theta}{Z^2} E_{aq} \quad (18) \text{ AMP. 18}$$

EXCITER

$$E_x = \frac{M}{L_e} \int [E_x - I_e (R_e + R_x)] dt \quad (19) \text{ AMP. 23'}$$

$$I_e = \frac{1}{M} E_x - S_e \quad (20) \text{ AMP. 22'}$$

$$R_x = [E_a - E_R] \frac{100}{.035 + 1} \quad (21) \text{ AMP. 13'}$$

DAMPING TRANSFORMER

$$\frac{V_D}{E_x} = \frac{(.02)S}{1 + (.25)S} \quad (22) \text{ AMP. 9', 10' AND 12'}$$

TURBINE

TORQUE EQUILIBRIUM EQUATION ROTOR :

$$J \frac{d\omega}{dt} + D\omega = \sum L = L_s - L_e \quad (23)$$

MULTIPLYING TORQUE BY SPEED (ω_0) $\rightarrow$ POWER

$$J \omega_0 \frac{d\omega}{dt} + D \omega_0 \omega = \omega_0 L_s - \omega_0 L_e = P_s - P_e \quad (24)$$

$$\text{OR } J \omega_0^2 \frac{d[\frac{\omega}{\omega_0}]}{dt} + D \omega_0^2 \frac{\omega}{\omega_0} = P_s - P_e \quad (25)$$

SUBJECT TASK XII
EQUATIONS FOR ANALOG MODEL

NORMALIZING AND LINEARIZING USING FINITE DIFFERENCES !

$$\frac{J\omega_0^2}{P_0} \frac{d}{dt} \left[\frac{\Delta\omega}{\omega_0} \right] + \frac{D\omega_0^2}{P_0} \left[\frac{\Delta\omega}{\omega_0} \right] = \frac{\Delta P_S - \Delta P_E}{P_0} \quad (26)$$

$$\frac{D\omega_0^2}{P_0} = \frac{D\omega_0^2}{L_0\omega_0} = \frac{D\omega_0}{L_0} = -\frac{\partial L}{\partial \omega} \frac{\omega_0}{L_0} \approx 1 \quad (\text{FOR NO LOSS CASE})$$

LET $\frac{J\omega_0^2}{P_0} = \tau$ (26) CONVERTS TO

$$\tau s \frac{\Delta\omega}{\omega_0} + [1] \frac{\Delta\omega}{\omega_0} = \frac{\Delta P_S - \Delta P_E}{P_0} \quad (27)$$

OR $\frac{\Delta\omega}{\omega_0} [\tau s + 1] = \frac{\Delta P_S - \Delta P_E}{P_0} \quad (28)$

OR $\frac{\Delta\omega}{\omega_0} = \frac{\Delta P_S - \Delta P_E}{P_0} \left[\frac{1}{\tau s + 1} \right] \quad (29) \text{ AMP, 23}$

THE TURBINE TIME CONSTANT $\tau = \frac{J\omega_0^2}{L_0\omega_0} = \frac{J\omega_0}{L_0} = \frac{[WR^2][\omega_0]}{308 L_0} =$
 $= \frac{(1606)(5489)}{(308)(3570)} \approx 8 \text{ SEC.}$

SPEED CONTROL SYSTEM

$$A = \frac{K}{0.25s + 1} [\omega_R - \omega] \quad (30) \text{ AMP, 21}$$

TURBINE STEAM CHEST

$$P_S = \frac{1}{.0035s + 1} W_S \quad (31) \text{ AMP, 24}$$

Fig. 1 Analog Circuit Diagram

APPENDIX 6.5
GENERATOR AND EXCITER SATURATION CURVES, EXCITER
CONTROLLED RESISTANCE CURVE, AND VECTOR DIAGRAM

GE SER. NO. 6999912
2500 KVA 1200 RPM 0.8 PF
4160 V, 2000 KW 347 ARMATURE AMPS
103 FIELD AMPS

4160 V, 0 KW 0 ARMATURE AMPS
50 FIELD AMPS

FIELD RESISTANCE = 0.773Ω

Fig. 2 SM-1 Generator Saturation Curve

Fig. 3 Exciter Saturation Curve

Fig. 4 Controllable Exciter Field Resistance (R_x) Vs. Exciter Potential Transformer Secondary Voltage

Fig. 5 Vector Diagram

APPENDIX 6.6
FUNCTION GENERATOR CURVES

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Fig. 6 Function Generator D3X, Generator Saturation Curve

Fig. 7 Function Generator B3X, Square Root for E_a

Fig. 8 Function Generator B2Y, Square Root for I_a

Fig. 9 Function Generator D2Y, Exciter Saturation Curve

6.7 POTENTIOMETER SETTINGS AND DECADE SETTINGS

Potentiometer Settings

Pot. No.	Setting (Nominal)	Into Amplifier	Amplifier Input Times	Parameter Formula or Description
5'	0.20	13'	10	Damping transformer gain. Varied for runs 1201, 1203, and 1205.
10'	.800	6'	10	Reference voltage for generator terminal volts.
11'	.90	19'	1	Initial conditions.
15'	.28	23'	1	Initial conditions.
16'	.313	22'	1	Slope of I_x vs. E_x . Exciter sat curve when unsaturated.
4	.25	12	1	$X'_d = .25$
10	1.0 (PF = 1)	10	1	$\frac{R_L}{(R_L^2 + X_L^2)^{1/2}} = \cos \phi$
	.8 (PF=.8)			Varied for runs 1030 to 1140.
11	0 (PF=1)	10	1	$(X'_q) \left[\frac{X_L}{(R_L^2 + X_L^2)^{1/2}} \right] = X'_q \sin \phi$
	.39 (PF=.8)		1	Varied for runs 1030 to 1140.
12	0 (PF=1) .6 (PF=.8)	18	1	$\frac{X_L}{(R_L^2 + X_L^2)^{1/2}} = \sin \phi$
13	.65 (PF=1) .525 (PF=.8)	18	1	$(X'_q) \left[\frac{R_L}{(R_L^2 + X_L^2)^{1/2}} \right] = \frac{X'_q \cos \phi}{X'_q} = .65$
14	.429	10	1	Load change. Varied for runs where load change is not 70-100% and back.
15	.429	18	1	Same as 14
16	.422	14	1	$(X'_q)^2 = (.65)^2 = .422$

Decade Settings

Decade gain is the inverse of the decade setting.

<u>Decade</u>	<u>Setting (Nominal)</u>	<u>Into Ampli- fier No.</u>	<u>Parameter Formula or Description</u>	<u>Calculation</u>
A	.991	19'	$T'_{do} \left(\frac{1 \text{ PU } E_x}{1 \text{ PU } E_{iq}} \right)$	$4.3 \left(\frac{19.3}{80} \right) = .991$
B	3.68	19'	$\frac{T'_{do}}{X_d - X'_d}$	$\frac{4.3}{(1.42 - .25)} = 3.68$
C	4.3	19'	T'_{do}	4.3
D	4.3	19'	T'_{do}	4.3
E	.86	23'	$\frac{L_e}{M_e}$	$\frac{30.6}{35.6} = .86$
G	.71	14'	$\frac{10}{P_e}$	$\frac{10}{14.1} = .71$
J	.003	13	$T_e/10$	$\frac{.03}{10} = .003$
K	.03	13	T_e	.03
P	.20	21	T_a	.2
Q	.20	21	T_a	.2
R	8	23	T_T	8
S	.32	23	$\frac{T_T}{K}$	$\frac{8}{25} = .32$
T	.32	23	$\frac{T_T}{K}$	$\frac{8}{25} = .32$
U	.1	24	T_{sc}	.1
V	.1	24	T_{sc}	.1

APPENDIX 6.8
ANALOG RUNS

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Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

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Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

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Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div.

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Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

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Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

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Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

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Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

1132

Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

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Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

1138

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Load
Current

1 Scale Division
Equals 6.25%

Generator
Terminal Voltage
Error
0.125%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

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Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

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Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

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Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

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Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

Load Current
6.25%/Scale Div.

Generator
Terminal Voltage
Error
1.25%/Scale Div

Controlled
Resistance in
Exciter Field
1 OHM/Scale Div

Generator Output
Power ($I_a E_a$)
6.25%/Scale Div

Turbine Speed
Error
0.312%/Scale Div

Direct Axis
Current
10.2%/Scale Div

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