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Dynamic Modeling of a Combined-Cycle Plant

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ABSTRACT

Greater use is being made of dynamic simulation of energy systems as a design tool for selecting control strategies and establishing operating procedures. This paper discusses the dynamic modeling of a gas-fired combined-cycle power plant with a gas turbine, a steam turbine, and an alternator--all rotating on a common shaft. A waste-heat boiler produces steam at two pressures using heat from the gas turbine flue gas. The transient behavior of the system predicted by the model for various upset situations appears physically reasonable and satisfactory for the operating constraints.

INTRODUCTION

Two 60-MW gas-fired combined cycle units are being erected at the Mirafiori works of the FIAT Company. Operating in parallel, both are very similar; therefore, the simulation program was written for one only.

The plant burns natural gas, which is expanded in a gas turbine. Exhaust flue gas from the gas turbine transfers heat to water in a waste-heat boiler, from which high-pressure (HP) and low-pressure (LP) steam are expanded in a steam turbine.

Dynamic simulation has been an important tool in overall plant design because the plant is designed to operate under some unique conditions:

- Normally, the plant is connected to the national grid (Parallel Operation), and a sizeable amount of power above that consumed in the Mirafiori area is exported to the grid. During this parallel operation, the plant experiences the load changes requested by the operating management.
- Another mode of operation (Island Operation) occurs when the plant is suddenly disconnected from the national grid and is required to rapidly shed load to match the power required by the Fiat factory.

In addition to the routine control features, the plant incorporates unique control characteristics to allow safe switchover and Island Operation.

Dynamic simulation was conducted to investigate whether the plant equipment and controls would operate safely and predictably under steady-state and transient conditions. Another purpose was to optimize the control system variables so that efficient plant operating procedures could be defined. As modeled, the system was highly nonlinear and characterized by strong interactions between the several variables. All important equipment and controls characteristics were digitally modeled and tested.

Steady-state simulation was performed using an iterative process. The dynamic simulation represented the pertinent equipment and controls by differential equations. They were solved incrementally with a numerical integration scheme on a digital computer.

This paper describes the combined-cycle plant, its operating modes, and its control characteristics. The computer program used in the solution is briefly discussed; and numerical representation of the equipment, process, and control systems is described. Finally, the paper presents some of the results obtained from the simulation.

PLANT DESCRIPTION

Fig. 1 is a schematic of the combined-cycle plant. Natural gas is burned in a compressor-turbine system, where the HP combustion products are expanded in a gas turbine. Airflow through the gas turbine compressor is a function of air temperature and machine speed. The gas turbine exhaust gas is routed through a waste-heat boiler for steam production. The waste-heat boiler produces HP and LP steam for expansion in a steam turbine. Additionally, hot air from the compressor produces LP steam in a waste heat exchanger. The exhaust air cools the turbine blades.

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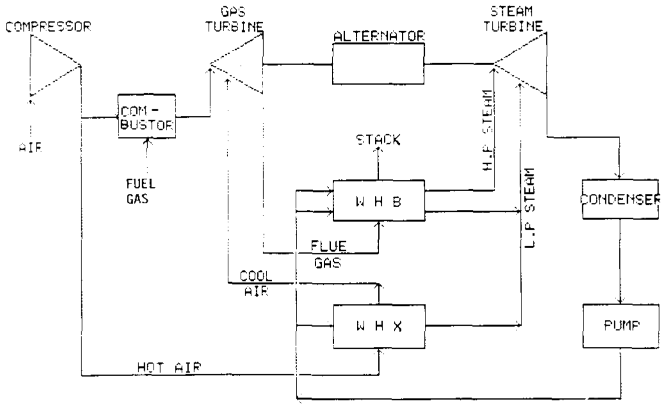

Fig. 1 Mirafiori Combined-Cycle Plant

The gas and steam turbines and the alternator use a common shaft for power production. At 100-percent power, the gas and steam turbines generate approximately 37 and 23 MWe respectively.

Fig. 2 shows details of the waste-heat boiler and the steam turbine. Heat to the HP and LP water/steam circuitry is supplied by the exhaust flue gas from the gas turbine. Feedwater from the condenser is heated in an LP preheater and LP economizer before it enters the LP drum. A recirculation pump withdraws saturated water from the drum, and steam is produced in the LP evaporator. The saturated steam from the LP drum is heated in the LP superheater and combined with the LP steam from the waste heat exchanger before entering the LP section of the steam turbine. Water is also drawn from the LP drum for feedwater to the HP drum via an HP economizer. A recirculation pump withdraws HP saturated water from the HP drum, and steam is produced in the HP evaporator. Saturated steam from the HP drum is superheated in the HP superheater and routed to the HP section of the steam turbine for expansion.

CONTROL SYSTEM

In Parallel Operation with the national grid, the combined cycle operates either under power control or under droop control on speed. In both cases, a setpoint change is performed through a ramp only. The ramp slows the variations in HP steam superheat temperatures that would cause thermal stress in the steam turbine, affecting its life.

In the power-control case, the measured variable is the total power produced by the cycle; in the droop-control case, the measured variable is the machine speed, which is set by the national grid. Power control is by a Proportional-Integral-Derivative (PID), while droop control is performed through a gain optionally corrected by a lead/lag compensator, but essentially without any integral action. The final action on the control valve is rate limited.

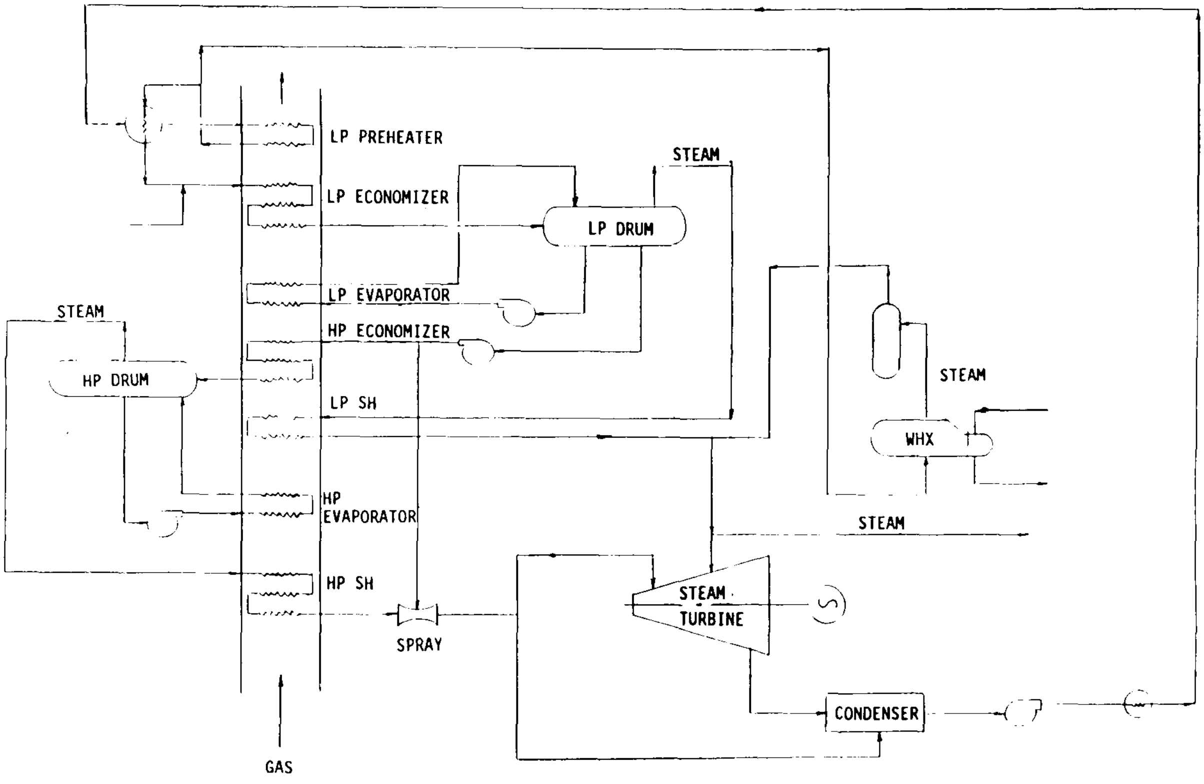

Fig. 2 Steam System--Fiat Mirafiori Plant

When the combined cycle is in Island Operation, three main control modes are possible on the gas turbine:

- Speed droop control (proportional and lead/lag compensation)
- Speed control (PID)
- Bypassed power control.

In the bypassed control mode, the power setpoint is biased to force the gas turbine toward a larger share of the total load, and the extra steam generated bypasses the steam turbine. The load to the gas turbine is filtered so that the steam turbine takes priority, using the bypassed amount as a buffer.

The steam turbine is under droop control by means of the HP steam inlet valve. There are three basic control loops for the steam system (Fig. 2):

- Level loop
- Temperature loop
- Pressure loop.

The HP and LP level loops ensure that the water level in the drum remains within certain limits under all steady-state and transient conditions. The water levels in the HP and LP drums are controlled by regulating feedwater flow. Each drum has two valves operating in split range to cover the various operating conditions.

An anticipated response is obtained in the HP drum by resetting the boiler feedwater flow controller with HP steam flow to the turbine, corrected for level controller demand.

The temperature loop controls the temperature of the HP superheated steam entering the steam turbine. Using a PI controller, the water from the HP feedwater pump is sprayed to maintain the superheated steam below a set temperature.

Fig. 3 is a schematic of the HP and LP steam pressure loops. Possible overriding of the HP steam inlet valve position by speed control is also indicated.

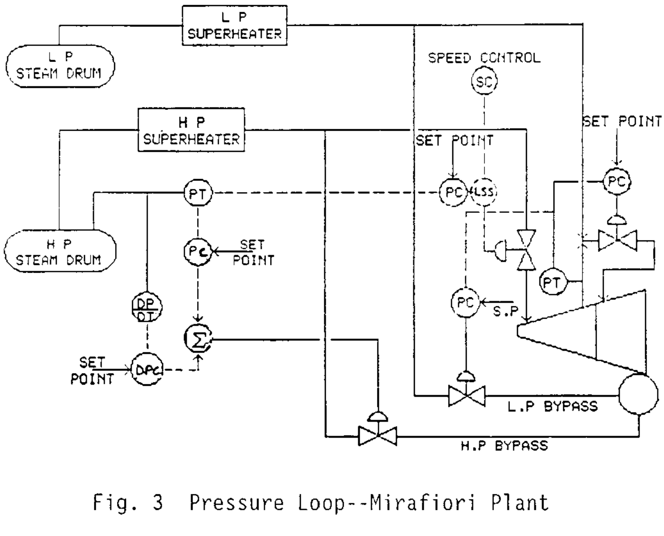

Fig. 3 Pressure Loop--Mirafiori Plant

Under Parallel Operation the machine speed is set by the national grid, so that only the pressure loop is effectively active; the pressure in the HP steam drum is maintained by operation of the steam turbine (i.e., the pressure is not fixed and varies according to the steam turbine operating load). However, HP drum pressure is allowed to float only above a minimum value; this value is maintained at lower loads by throttling the steam turbine inlet control valve. Therefore, the HP steam throttle valve is fully open when HP steam drum pressures are above the minimum value; it begins to close as the drum pressure drops further. A bypass line upstream of the HP steam throttle valve protects from overpressure. The bypass valve opens, allowing HP steam to flow in the HP bypass line to the condenser when the HP drum pressure is higher than a set value. The bypass valve also opens if the HP steam pressure increases at a fast rate. LP steam pressure control is similar, except that steam pressure rate control is not present.

STEADY-STATE SIMULATION

Steady-state simulation is necessary at several load conditions, since they represent the initial conditions for dynamic events. It was performed with three logical blocks (gas turbine, waste-heat boiler, and steam turbine).

Gas turbine steady-state performance was derived from manufacturer's curves for specific design conditions and fuel. The independent variables considered were the fuel gas valve lift and ambient air temperature. The flow rate of air through the gas turbine compressor is a function of air temperature and machine speed. Air compressor discharge pressure is an intermediate variable correlated by manufacturer's curves to gas turbine power production and to ambient air temperature. This pressure was used to correct the fuel gas flow rate through the valve.

The output of this gas turbine block consisted of brake power and exhaust gas flow and temperature. Exhaust gas characteristics were the input to the waste-heat boiler and steam turbine blocks. The solution of the algebraic system of the waste-boiler, constituted by thermal and hydraulic balances, was derived iteratively. Heat transfer and steam thermodynamic properties were evaluated using standard correlations. Valve and pump characteristics and steam turbine and condenser performances were derived and fitted from manufacturers' data.

Steady-state trends of major plant variables as a function of load have already been presented (Dorigo, 1988).

DYNAMIC SIMULATION

In the dynamic model, thermal balances were written through differential equations. Various equipment time constants were determined at every integration step on the basis of variables relevance.

Time constants of valves, supplied by the manufacturers, and time lags from piping volumes between different elements of the waste-heat boiler were modeled. These resulted in a series of linear differential equations, with time as the independent variable and thermodynamic variables for the components as the dependent variables. Additional differential and algebraic equations--representing proportional, integral, derivative, and lead/lag compensation controls--and algebraic equations describing hydraulic balances between appropriate volumes were superimposed on the differential equations.

Machine performance was calculated by coupling steady-state values, updated at every integration step with time constants specified by the manufacturers. This simulation procedure resulted in approximately 100 differential and algebraic equations.

The numerical integration was performed by means of Euler's method as part of a public domain software package (Lehigh University, 1979). The time increment chosen in each integration step is estimated automatically in the integration algorithm, based on a user-supplied tolerance for integration error and minimum integration step.

RESULTS

The dynamic simulation program was tested by making several runs for different transient conditions in the combined cycle. The transient values of the pertinent cycle parameters were plotted to review their behavior. Typical parametric plots for two transient conditions are presented in the following sections.

Parallel Operation

In this simulation a load reduction from 100 to 50 percent is followed by approximately 600 seconds of stabilization at 50-percent load and then by recovery of load to 80 percent under power control.

Figs. 4 through 7 give the simulated response of key system parameters; the variation of total alternator power and gas and steam turbine power is shown in Fig. 4. For power control, the gas turbine attempts to compensate for the slower response of the steam turbine by overshooting its own steady-state load level.

Fig. 5 presents the lift of the fuel gas valve and of the HP and LP steam turbine inlet valves. HP and LP steam inlet valve behavior reflects the control strategy that allows pressure fluctuations in the HP and LP circuits only above minimum steam pressures. The HP and LP steam drum pressures are shown in Fig. 6.

Fig. 7 depicts the temperatures of the gas turbine exhaust and the HP superheated steam. As shown in the figure, the thermal inertia of the superheater tubes causes the steam temperature to be higher than the flue gas temperature during the transient.

Island Operation

A switch from Parallel to Island mode, with a rejection of 16.5 MW of power under speed control, is simulated in the short-term transient. Fig. 8 shows that the gas turbine absorbs the largest portion of power variation. Fig. 9 shows the transient frequency.

The fuel gas valve and the HP and LP inlet valve lifts are plotted in Fig. 10. The quick closing and opening of the valves do not cause appreciable variations in steam drum pressures because of the relatively large volume of steam available in drums and piping (Fig. 11).

Results of other dynamic simulations are presented elsewhere (Maderni et al., 1989).

SUMMARY

Dynamic simulation of a gas-fired combined-cycle plant was performed during the design stage to assist in selecting a control philosophy and evaluating safety for various planned and upset operating scenarios. The results of the dynamic simulation appear reasonable and confirm that the selected equipment and controls will result in safe and efficient operation of the plant under all anticipated steady-state and transient conditions. The simulation proved a valuable design tool for evaluating system response to competing equipment parameters and control schemes. The work presented in this paper illustrates that dynamic simulation should be used as an integral part of an overall plant design process for combined-cycle and other similar systems.

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REFERENCES

Dorigo, E., Alloni, G., and Bressan, L., "The FIAT MIRAFIORI Cogeneration Units," 1988 ASME Cogenturbo, 2nd International Symposium, Montreux, Switzerland, p. 193.

Lehigh University, 1979, "DSS/2: Differential System Simulator, Version 2."

Maderni, L., Icardi, G., and Fontana, M., 1989, "Control System for a Combined Cycle," submitted for acceptance at the ASME International Gas Turbine & Aeroengine Congress & Exposition.

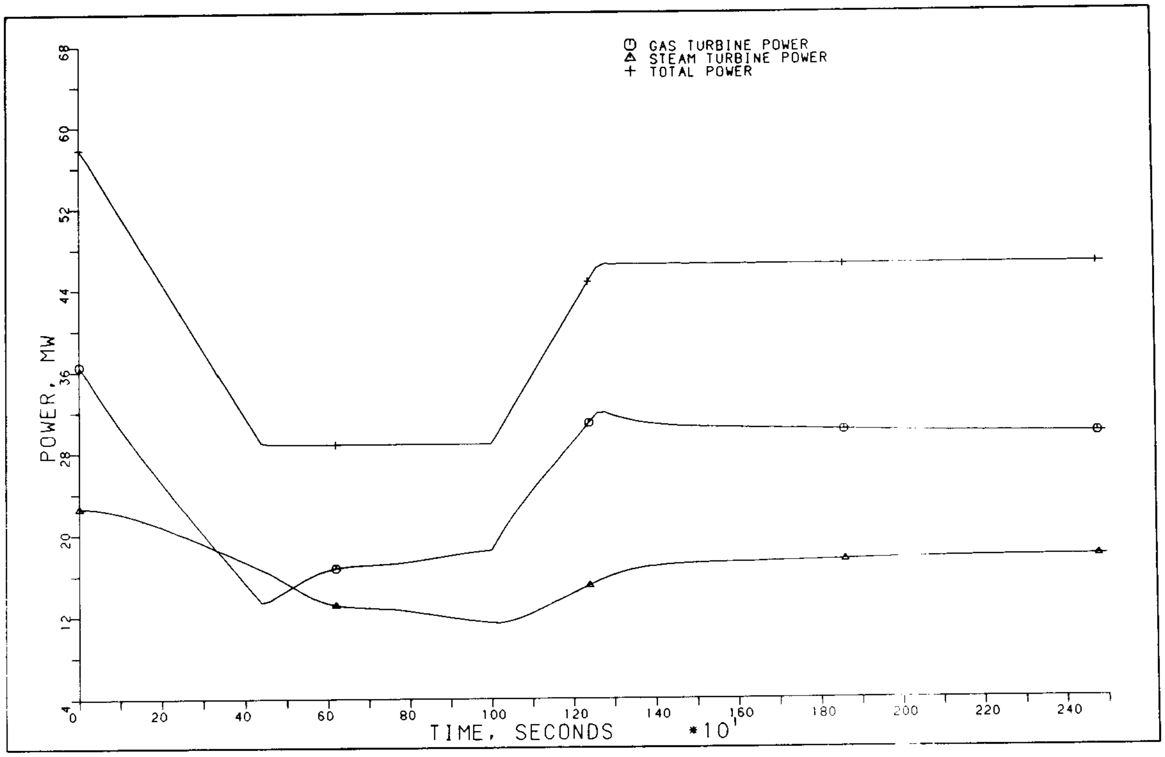

Fig. 4 Variation of Total Alternator Power and Gas/Steam Turbine Power

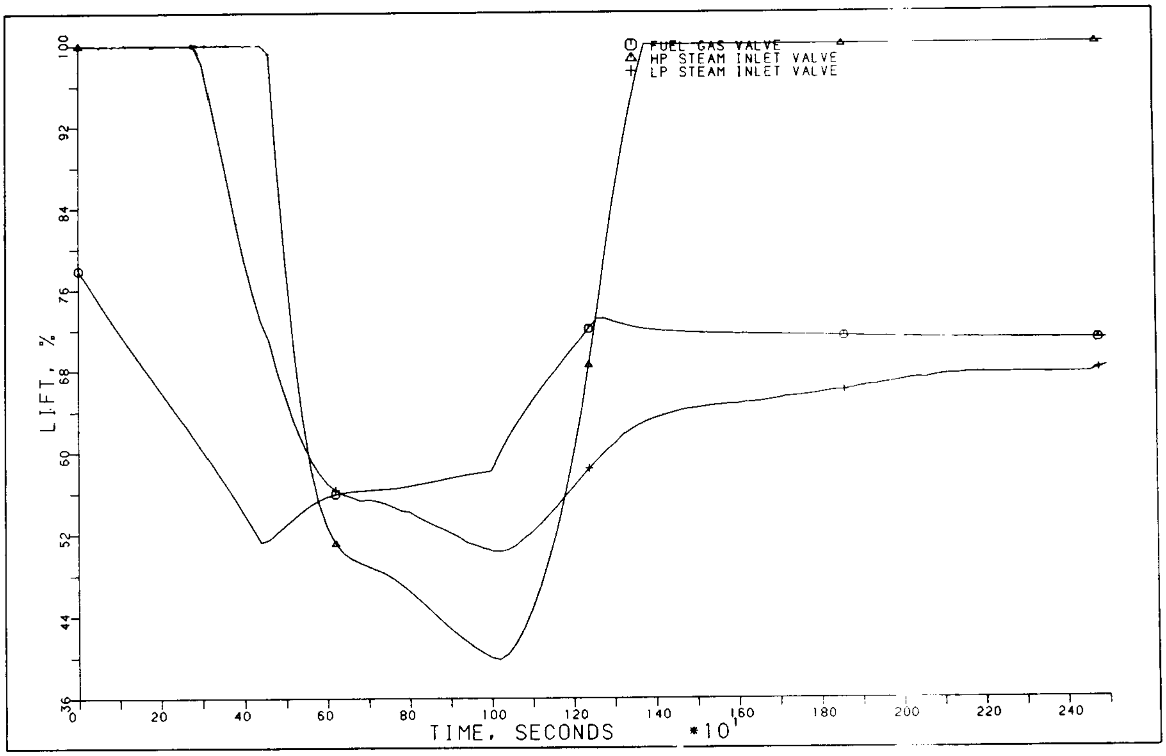

Fig. 5 Lift of Fuel Gas Valve and HP/LP Steam Turbine Inlet Valves

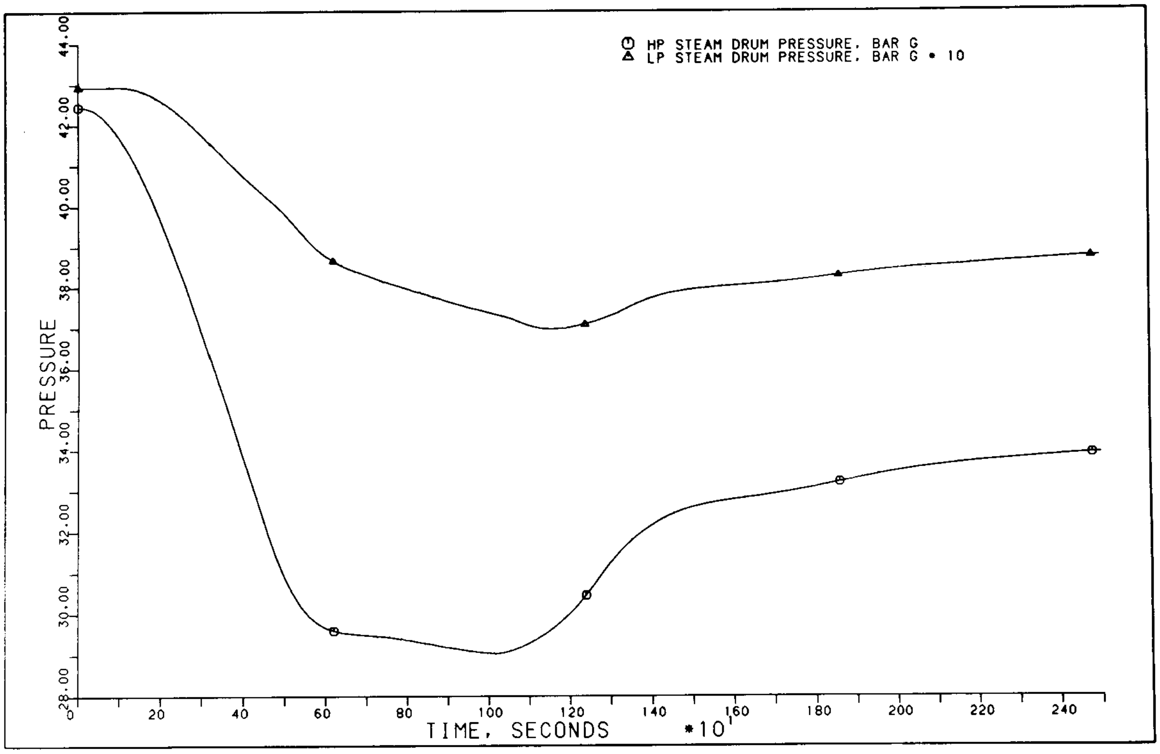

Fig. 6 HP/LP Steam Drum Pressures

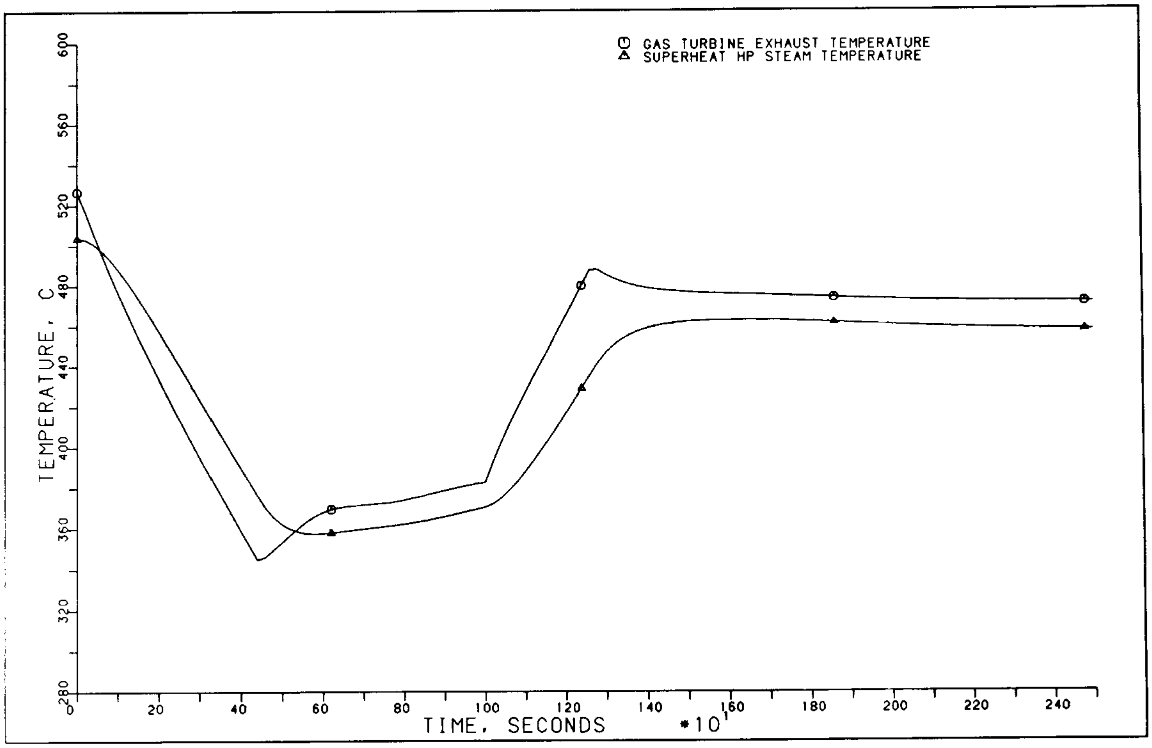

Fig. 7 Temperatures of Gas Turbine Exhaust and HP Superheated Steam

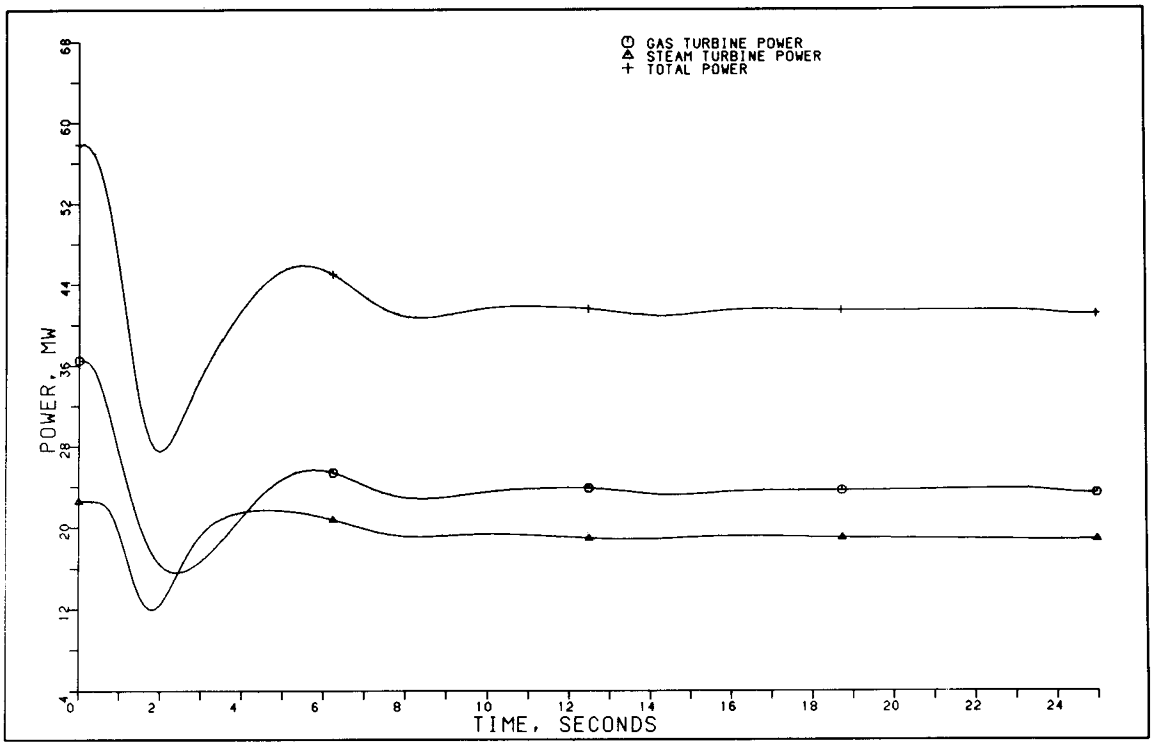

Fig. 8 Gas/Steam Turbine and Total Power Variation

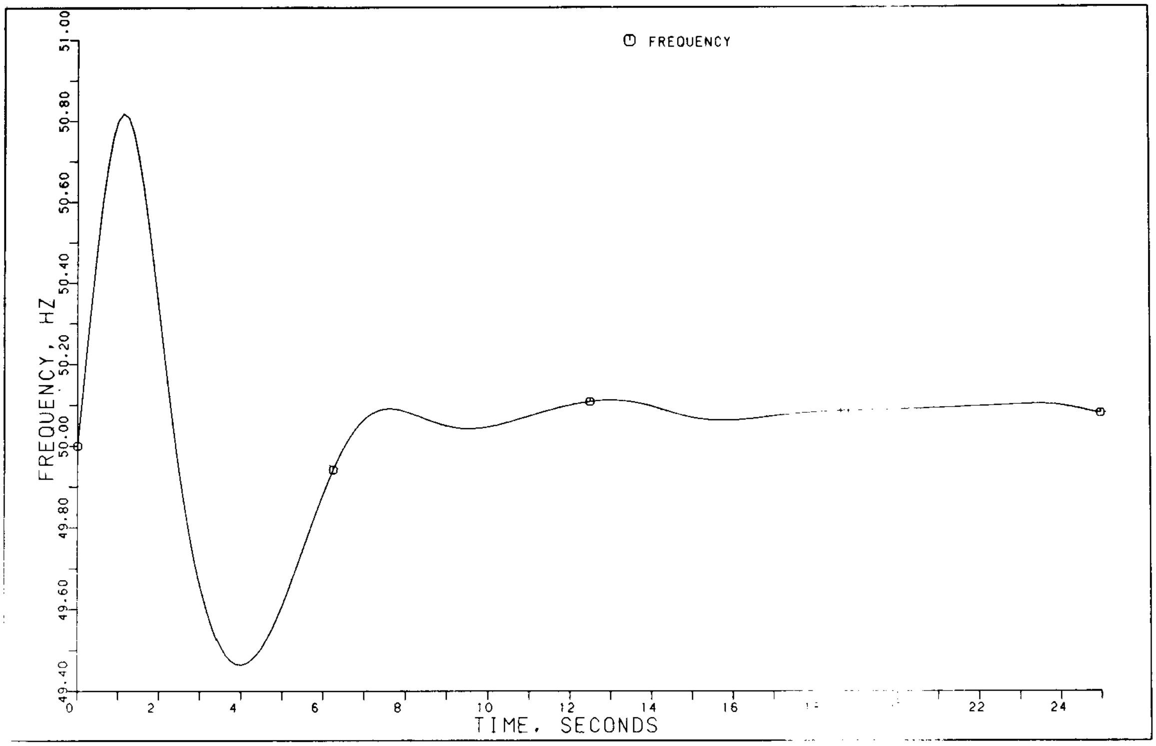

Fig. 9 Transient Frequency

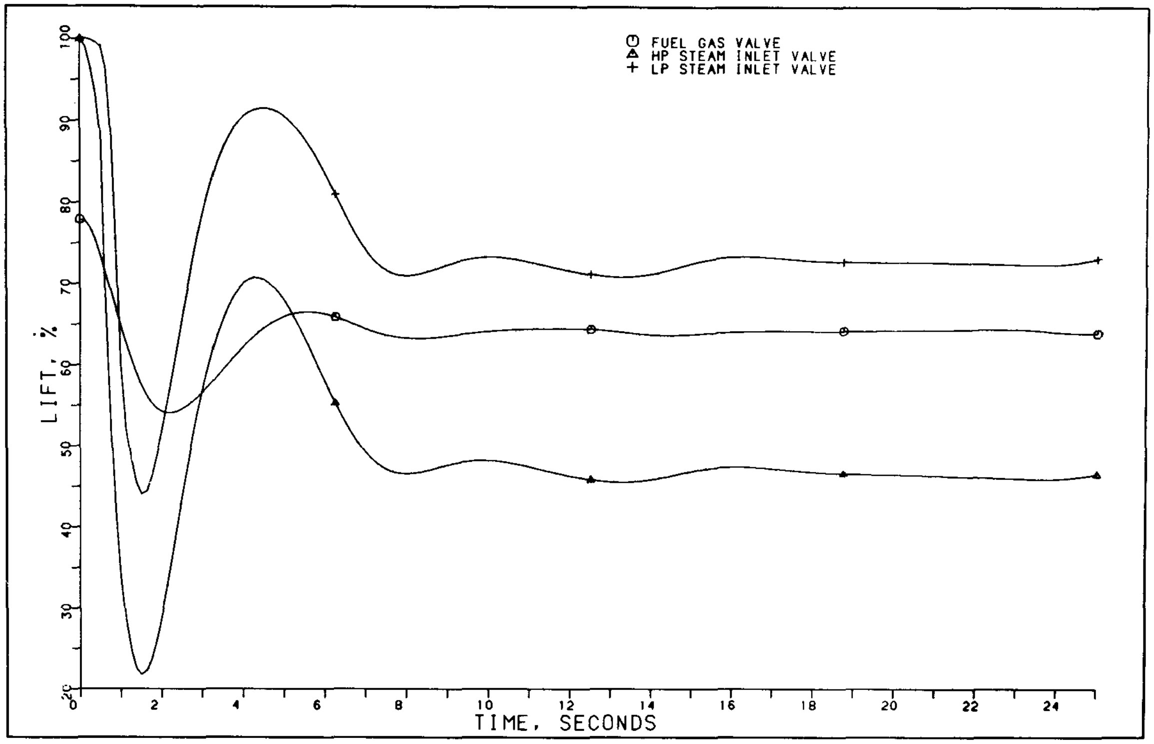

Fig. 10 Plots of Fuel Gas and HP/LP Inlet Valve Lifts

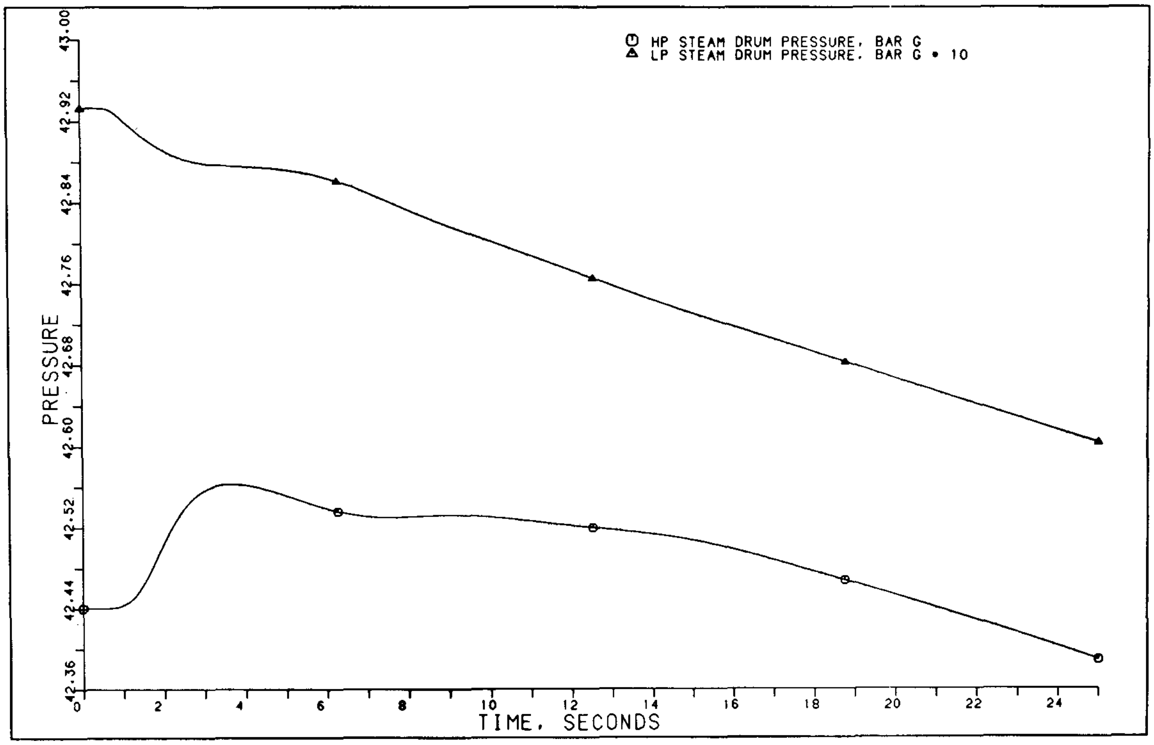

Fig. 11 HP/LP Steam Drum Pressures