Conventionally-Based Control Strategies For Combined-Cycle MHD Steam Power Plants

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CONVENTIONALLY-BASED CONTROL STRATEGIES FOR COMBINED-CYCLE MHD-STEAM POWER PLANTS

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Abstract

A representative set of conventionally-based control strategies is applied to a first-principle dynamic model of an ETF-sized combined-cycle MHD-steam plant. Depending on how major control signals are formed, the overall control strategies are similar to conventional boiler-following, turbine-following, or coordinated control. Variations of control of combustion gas recycling appear within each major control strategy. Examples of plant dynamic response under each of the three major strategies are presented and discussed.

I. Introduction

This paper presents descriptions and results of conventionally-based control policies applied to a first-principle dynamic model of a combined-cycle MHD-steam power plant. The purpose is to determine control structure and controller values which result in safe, stable, fast, and smooth transitions between operating points, subject to necessary constraints on system variables. These models and studies are generally applicable to plants of Engineering Test Facility (ETF) and commercial sizes, and of various designs.

The complete plant model is built up from component and subsystem models, each of which is ultimately based on physical descriptions of behavior. The steam plant is described by first-principle dynamic equations of physical laws.[1-5] Parameters and variables that appear in the actual plant (e.g., temperatures of steam, metal, and combustion gases, pressures of steam and combustion air, mass flow rates, control valve areas, etc.) also appear in the dynamic model. The MHD topping cycle model is nondynamic because its time constants are so much shorter than those of the remainder of the system that for all purposes of current use, it exhibits instantaneous response. It appears as a set of algebraic curve-fits (called input-output models) which are derived from a data base generated by other detailed time-dependent models of specific MHD components.

II. MHD-steam Plant Model Features

The plant is ETF-sized, characterized by fired air preheater providing atmospheric air as oxidant at 3000°F (1922K). A non-reheat main steam turbine and a steam-driven oxidant compressor are included, both of which are supplied from the drum-type main steam system at 1300 psia (8.96 MPa) and 950°F (783K) throttle conditions. Nominal thermal input is 300 MW. Electrical output is 108.0 MW with 51.5 MW MHD power and 56.5 MW main turbine-generator power at 100 percent of design. In these respects, the plant modeled is similar to the AVCO preliminary ETF conceptual designs.[6]

The state variables of model operation are principally mass flow rates, pressures, temperatures, and power extraction at numerous pertinent points in the plant. The plant model is suitable for dynamic operation in the 50 percent to 110 percent range of rated electrical output, with the principal limitations being the range coverable by the combustor-nozzle-channel-diffuser subsystem model and the current range of steam-water modeling.

The combustor-nozzle-channel-diffuser (CNCD) has four flow related inputs controlled: oxidant flow, coal flow, seed flow, and oxidant preheat. Only oxidant flow is directly controlled during the tests presented. Coal flow and seed flow are forced to follow oxidant flow to maintain a .95 equivalence ratio and 1 percent seeding levels while oxidant preheat is fixed at 1922K.

The physical arrangement of the steam generating portion of the plant is shown in Figure 1, displaying the assumed locations of all significant steam generator components. Of salient interest is the location of recycled combustion gasports just preceding the secondary (finishing) superheater and above the seed taps at the bottom of the secondary furnace. Thus recycled gas produces two immediate effects: (1) an increase in gas flow through all portions of the steam generator downstream of the radiant boiler, including both superheater sections, the low-temperature air heater (LTAH), and the economizer, and (2) a depression in the temperature profile of the combustion gas downstream of the injection ports.

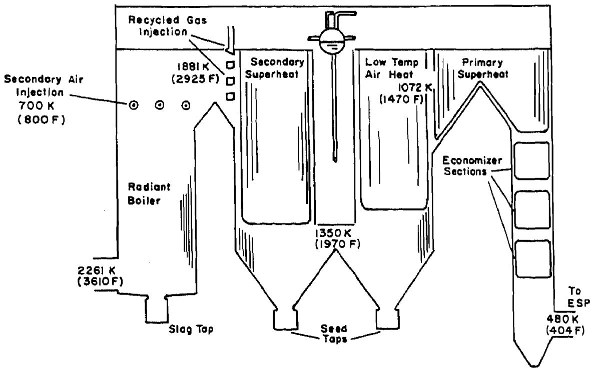

Figure 1. Simplified Steam Generator Elevation

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The effect of increased gas flow and depressed gas temperature on the steam generator system is to increase heat transfer to the convective units mentioned above. The gas-side heat transfer equations of the units are[1,4,7]

$$QG_{SECSH} = .00141(\overline{T}_{gas} - \overline{T}_{met})W_{gas}^{0.6} + .561 \times 10^{-12}(\overline{T}_{gas}{}^4 - \overline{T}_{met}{}^4) \quad (1)$$

for the secondary superheater, and

$$QG_{LTAH} = .00390(\overline{T}_{gas} - \overline{T}_{met}) \quad (2)$$

$$QG_{PRISH} = .0102(\overline{T}_{gas} - \overline{T}_{met}) \quad (3)$$

$$QG_{ECON} = .0160(\overline{T}_{gas} - \overline{T}_{met}) \quad (4)$$

for the low-temperature air heater, primary superheater, and economizer, respectively.

$\overline{T}_{gas}$ and $\overline{T}_{met}$ are the average gas temperatures and metal temperatures (°K) appropriate to each unit, while W_{gas} is gas flow in Kg/sec.

Steam/water-side heat transfer is given by the equations

$$QS_{SECSH} = .00645(\overline{T}_{met} - \overline{T}_{steam})W_{steam}^{0.8} \quad (5)$$

$$QA_{LTAH} = .0118(\overline{T}_{met} - \overline{T}_{air})W_{air}^{0.8} \quad (6)$$

$$QS_{PRISH} = .0221(\overline{T}_{met} - \overline{T}_{steam})W_{steam}^{0.8} \quad (7)$$

$$QW_{ECON} = .0416(\overline{T}_{met} - \overline{T}_{water})W_{water}^{0.8} \quad (8)$$

where the symbols are self-explanatory. The coefficients of equations 1-8 incorporate emissivity, average film transfer coefficients, surface area, and shape factor. Additional equations contain information on metal mass, metal specific heat, steam/water/air volume and enthalpy-temperature relations.

Within the normal operating range of the plant, the increase in gas-side heat transfer due to greater combustion gas flow dominates the drop in heat transfer due to decreased temperature differences. Thus gas recycling can maintain the important main steam conditions at low loads by providing increased heat transfer to superheat and economizer surfaces.

A second effect of gas recycling having particular interest is that gas temperature at the bottom of the secondary furnace can be driven downward (but not upward) from the normal (non-recycling) temperature. At the upper end of normal operation (above 70% load), gas recycling can be used to depress the secondary furnace exit gas temperature to 1350K, just above the fusion temperature of potassium sulfate (1342K). Whether this will be effective in seed product recovery has been a subject of considerable discussion, but the control action is feasible. The efficacy of such control will not be known until after the heat-recovery seed-recovery (HRSR) test facility is operated.

It is important to note that throttle steam temperature control calls for gas recycling at low loads, tapering off as load increases, while seed condenser exit gas temperature control calls for recycling at high loads, tapering off as load decreases. Thus the two objectives of gas recycling are in direct conflict. Examples of both modes of control (and of no control) are given in subsequent sections, and can be judged in the context of overall plant behavior as well.

III. Control Points and Controller Structure

While sharing similarities with conventional fossil-fired steam plants, MHD-steam plants have certain fundamental aspects of control possibilities and problems that set them apart. The principal differences are:

- The firing rate produces immediate power through enthalpy extraction in the MHD channel, a feature not existing in conventional plants.
- Firing power is required in the form of steam to operate the air compressor drive turbine. This is about 22 to 25 percent of total steam generation in steady-state.
- Burner tilts for superheat and steam generation control are absent, leaving gas recycling as the major possibility for such control.

The fundamental flow paths and flow control points are shown in Figures 2, 3, and 4. The two major control points are the main turbine governor value (C_3) and the air compressor turbine governor value (C_4). One other control point, the gas recycle damper, is quite significant with regard to the wide choice of control policies that may be applied to it. Its clear and immediate effects on the system are discussed above. Its unexpected effects will be discussed in the next section.

Other control points are no less significant in their effect on proper plant operation, but the range of control policies that can be applied to them is very restricted in practice or is restricted for this model. A moderate exception is the drum water level controller, which drives the boiler feed pump turbine. For this model it is a feed forward controller on main steam pressure, a proportional-integral controller on in flow-out flow difference, and a deadband controller on measured level. Control points such as spray attemperator, secondary air injection, and water wall circulation are less significant in operating impact, producing secondary effects on stability.

Considering the needs of plant responsiveness and plant integrity, the two most important variables are net plant power output (QE_4) and main steam pressure (PS_5). Therefore, control signals that actuate the turbine governor values will be formed from these physical variables. The need to meet power demands is clear, especially if the plant is part of a modern dispatch grid

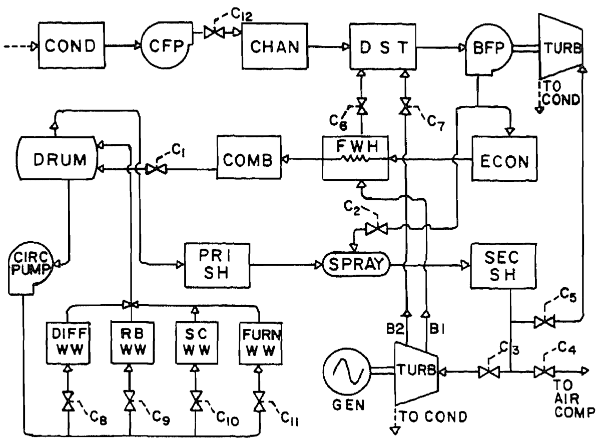

Figure 2. Steam-Water Path with Control Points

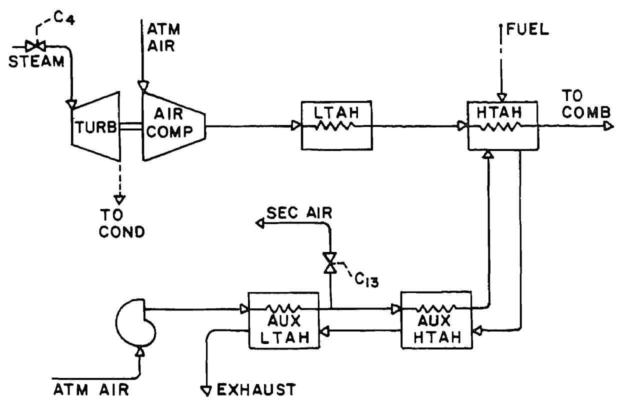

Figure 3. Air Path with Control Points

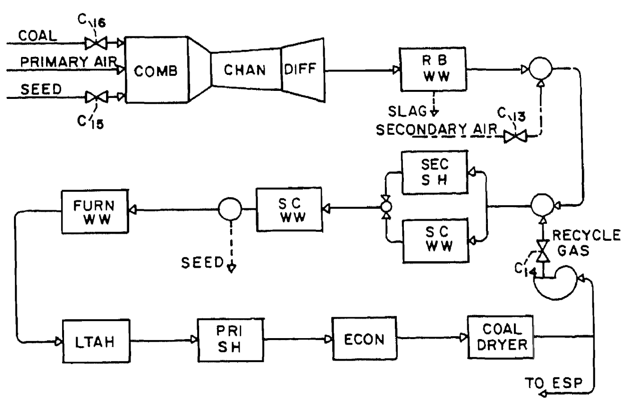

Figure 4. Combustion Gas Path with Control Points

with its long tie lines and interconnected system operation. The identification of main steam pressure as the principal integrity measure is based on the fact that without adequate steam pressure, system functions shut down. With the remainder of the plant controls operating in normal closed-loop manners (e.g., spray attemperator fixing an upper limit on the main steam temperature, boiler feed pump control setting drum level, etc.), the simplified main control loops appear as in Figure 5, with turbine value areas as control points.

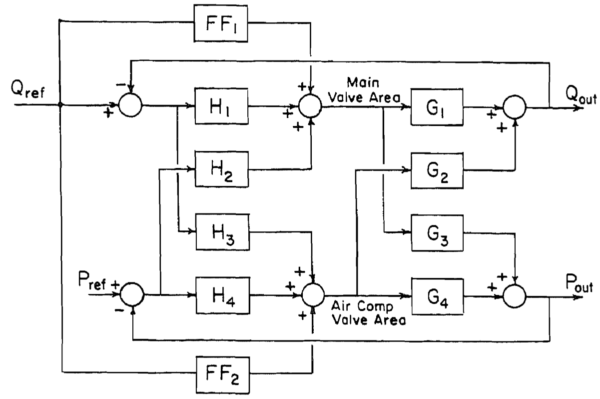

Figure 5. Main Turbine Valve and Air Compressor Turbine Valve Control Structure, MHD-Leading when H_2 and H_3 non-zero; $H_1 = H_4 = 0$. MHD-Following when H_1 and H_4 non-zero; $H_2 = H_3 = 0$. Feed-forward may be present in either mode.

The power reference input is megawatt demand (Q_{ref}) and the controlled output is combined MHD-steam megawatt production (Q_{out}). P_{ref} is the throttle steam pressure reference, and P_{out} is the actual throttle pressure. Thus, the major loop is from Q_{ref} to Q_{out} and returning through the upper feedback path, while another loop is from P_{ref} to P_{out} and return. Plant dynamics are represented by G_i, i = 1,2,3,4, in which G_1 and G_2 embody the effects of main turbine valve area on power production and throttle pressure, respectively, while G_3 and G_4 represent the effects of air compressor turbine valve area on power production and throttle pressure.

Proportional-integral-derivative (PID) controllers are placed in cascade between the error signal and the pertinent turbine valve and are represented by H_j, j = 1,2,3,4. In general form,

$$H_j = K_{j1} + \frac{K_{j2}}{s} + \frac{K_{j3}s}{s+a_j}.$$

For ease in modification of controllers, separate integrators are not used, having been combined into a single integrator with two inputs as in Figures 6 and 7. For all control points, integral controllers have logic preventing them from integrating the control signal beyond either upper or lower valve limits (anti-windup logic).

FF1 and FF2 are proportional feedforward controllers that immediately drive main turbine valves and air compressor turbine valves to nominal operating points in accordance with Q_{ref}.

Detailed schematic diagrams of the main generator turbine valve controllers and air compressor turbine valve controllers are shown in Figures 6 and 7, respcetively. They also include valve servo dynamics, rate limiting, and magnitude limiting characteristics. H_1 is identifiable as the collection of blocks at the top of Figure 6 (headed by block K_1) and H_2 is the collection of blocks in the middle of the figure (headed by K_{56}). FF_1 is composed of multiplier K_{FF1} and additive constant K_{FF2}. Similarly, H_3 is the group of blocks at the top of Figure 7 (headed by K_{60}), and H_4 is the group in the middle (headed by K_{61}). The feedforward block FF_2 consists of multiplier K_{FF3} and additive constant K_{FF4}.

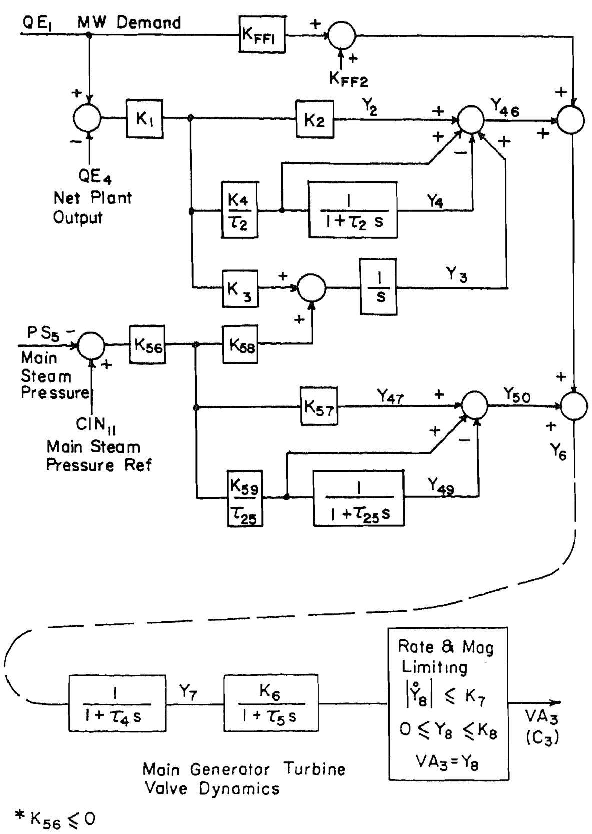

Figure 6. Main Generator Turbine Valve Control

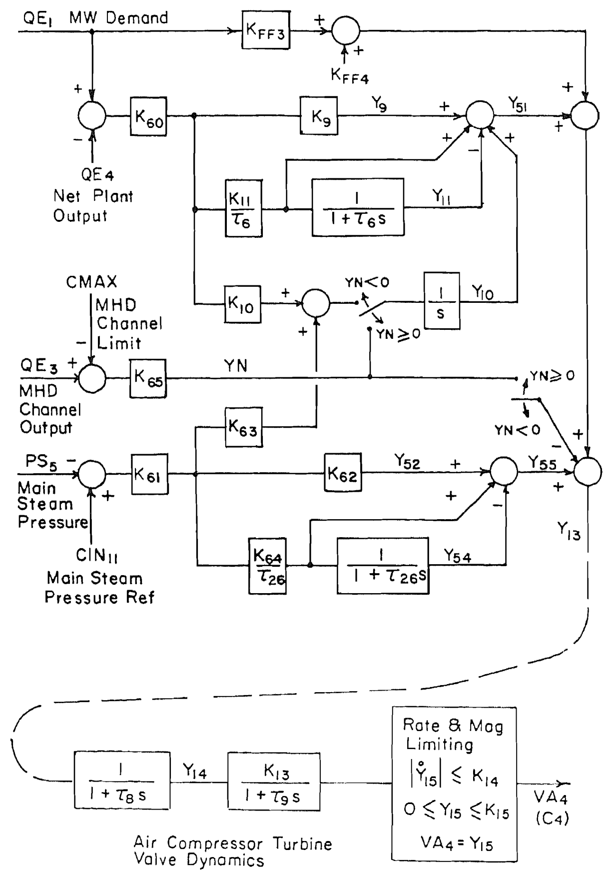

Figure 7. Air Compressor Turbine Valve Control

Two basic control modes are defined by the manner in which the main turbine valve and the air compressor valve are modulated. Figure 5 shows that three signals are used for such control: power demand (Q_{ref}), power error (Q_{ref} - Q_{out}), and throttle pressure error (P_{ref} - P_{out}). If power error is the signal controlling air compressor turbine valve area and throttle pressure error is the signal controlling main turbine valve area, the mode of control is labeled 'MHD-Leading,' since the MHD power train leads the steam bottoming plant by responding immediately to power generation error, leaving the steam plant to respond more slowly to changes in throttle steam pressure. It is similar in response to conventional turbine-following control--stable with slow settling of response. Referring to Figure 5, H_2 and H_3 controllers are providing the control signals for valve actuation, while H_1 = H_4 = 0.

When the controlling signals are interchanged, i.e., when throttle pressure error controls air compressor valve area and power demand error controls main turbine valve area, the mode of control is labeled 'MHD-following.' The steam plant leads in response to the power demand, thereby dropping the throttle pressure and creating an increased firing rate signal which the air compressor governor valve (and hence the MHD power train) follows. This control is similar to conventional boiler following control--rapid response from the steam plant, higher overshoots, and tendencies toward instability.

Either control strategy may be augmented by feedforward control asserted by the power demand. When feedforward is applied, either or both turbine governor valves are driven rapidly to their nominal steady-state values corresponding to the new demand point. Controllers FF_1 and FF_2 of Figure 5 provide this action.

Combination of both MHD-leading and MHD-following control yields a coordinated control mode, which has desireable features of both types of control.

Because the plant involved is representative of the ETF and channel integrity is probably of high interest, it was deemed advisable to provide a control mode that limits stress imposed on the channel. The channel stress measure was taken to be MHD electrical output (QE_3) (it could as well have been combustion gas flow or diffuser outlet temperature). When QE_3 exceeds an arbitrary value (CMAX), the dual mode controllers for the air compressor turbine valve, H_3 and/or H_4, switch from the normal error signal to a channel overshoot error signal (YN), thereby limiting air compressor turbine drive. The effect on stability can be significant since channel output is also basically the steam plant firing rate.

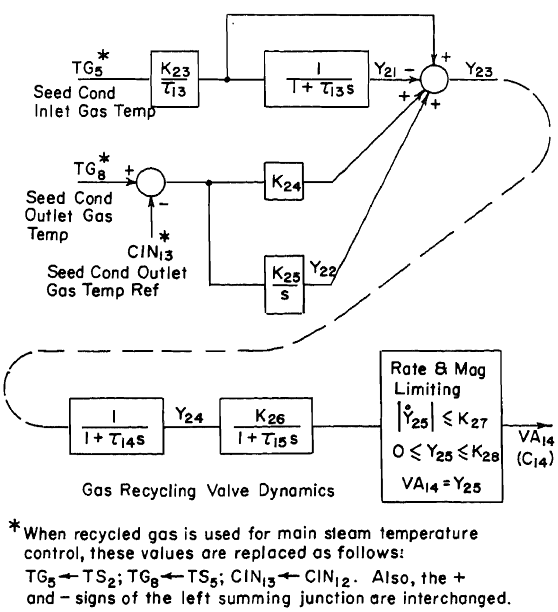

Figure 8. Combustion Gas Recycling Valve Control

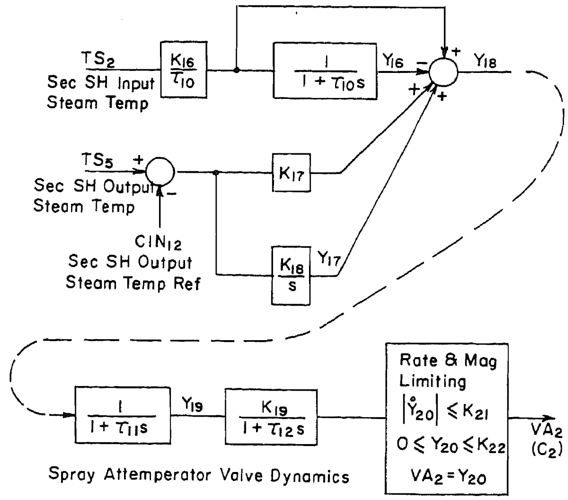

Figure 9. Spray Attemperator Valve Control

IV. Results of Control Policy Applications

Virtually endless variations of control policies can be applied to the combined-cycle plant, each of which has its distinguishing response characteristics. Examples of the three control strategies discussed above are shown. Table 1 gives control parameters that determine the strategy while Table 2 gives important parameters that are invariant among strategies.

Table 1. Strategy-Determining Control Constants

Constant	Coordinated Control	MHD Leading	MHD Following
K_1	100.0	0.0	100.0
K_{56}	-0.5	-1.0	0.0
K_{60}	1.0	1.0	0.0
K_{61}	1.0	0.0	1.0

Table 2. Strategy-Invariant Control Constants

K_2	0.002	K_{FF4}	0.511	K_{26}	1.0
K_3	0.00005	K_9	0.005	K_{57}	0.5
K_4	0.0	K_{10}	0.00025	K_{58}	0.002
K_6	4.42	K_{11}	0.0	K_{59}	0.0
K_{FF1}	0.00685	K_{13}	1.276	K_{62}	0.5
K_{FF2}	0.267	K_{23}	0.0053	K_{63}	0.002
K_{FF3}	0.00448	K_{24}	0.0053	K_{64}	0.0

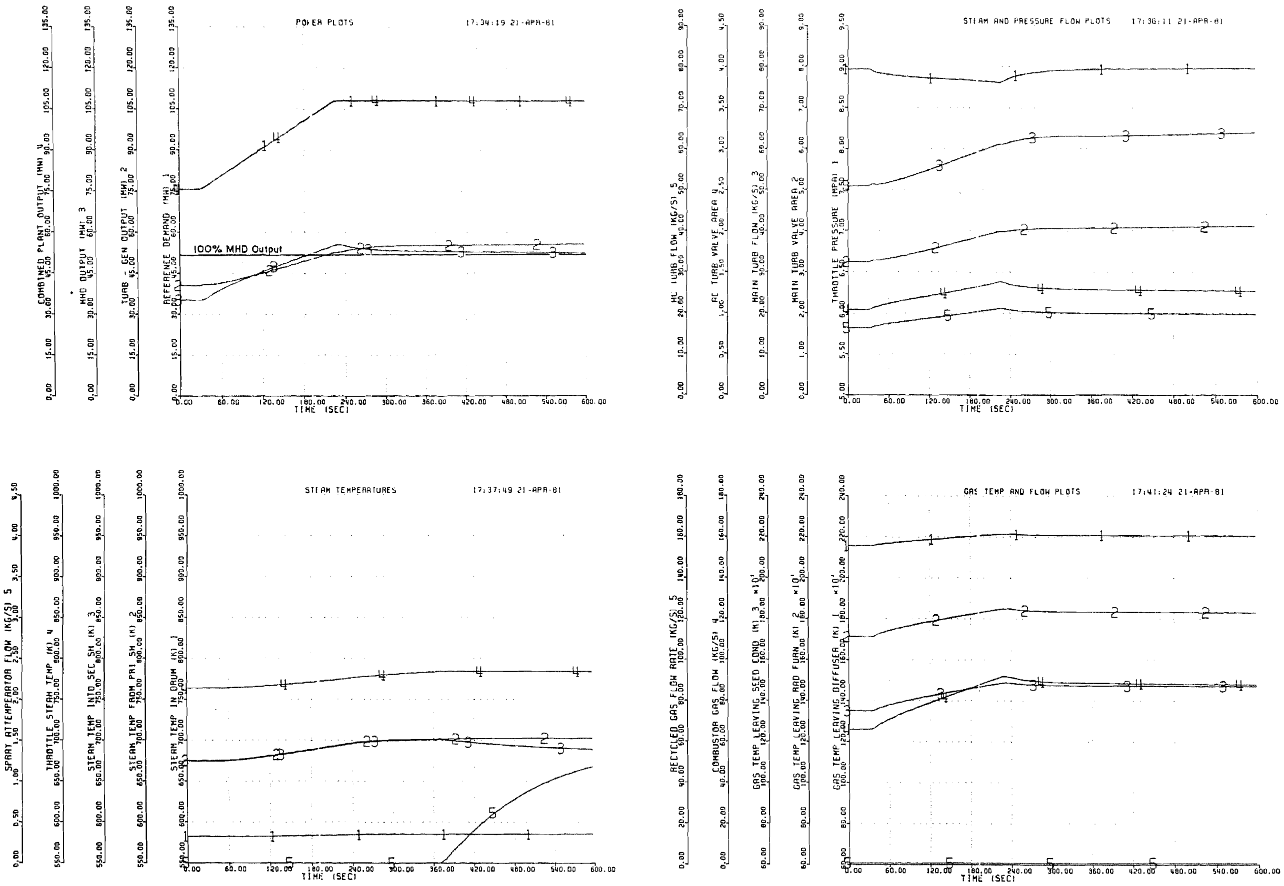

Figure 10. Fully Coordinated Control. No Channel Limiting. No Gas Recycling.

The system was subjected to both ramp-up and ramp-down (at ten percent per minute rates) between limits of 100 percent rated output and 70 percent rated output. A ramp-up of demand is shown since this direction of load change stresses the plant capability more severely than does a ramp-down of demand.

Control strategy 1 (Figures 10 - 12) is fully coordinated control without MHD channel limiting, having variations in the control modes for gas recycling. It is also the only strategy for which steam condition plots and gas condition plots are shown. Power plots and steam flow plots are shown for all control strategies.

Demand tracking ability of coordinated control is excellent, which is typical of strategies in which the main turbine is responsive to megawatt demand (MHD-following characteristics). Indeed, dynamic response of the plant may be less a limiting factor under such control than are the maximum temperature gradients that the turbine can withstand. Channel output exceeds 100 percent rating (51.5 MW) for much of the time, reaching a peak of 107.8 percent (55.5 MW) at the end of the ramp. This behavior has implications for air heater sizing as well as channel safety.

The 100 percent channel output level is shown in all power plots. Throttle pressure is well behaved but throttle temperature is depressed by 20K at 70 percent load, rising to set point 340 seconds after ramp application. Meanwhile, gas temperature at the exit of the seed condenser furnace rises from 1350K (the desired value - a coincidence) to a peak of 1520K at the end of the ramp, then settling to 1470K after 10 minutes.

Gas recycling for throttle steam temperature control (Figure 11) produces soft limiting of MHD channel output without imposition of hard limiting through the dual-mode controller. This response is characteristic since it has occurred in every application of gas recycling for steam temperature control, independent of the overall control strategy (coordinated, MHD-leading, MHD-following). Throttle pressure is not so well behaved, showing a sizeable hump at 240 seconds, while temperature is well controlled, as expected. Seed condenser gas exit temperature is erratic. Again, these general responses are characteristic of gas recycling controlled by main steam conditions.

Gas recycling for seed condenser gas temperature control (Figure 12) causes a significant

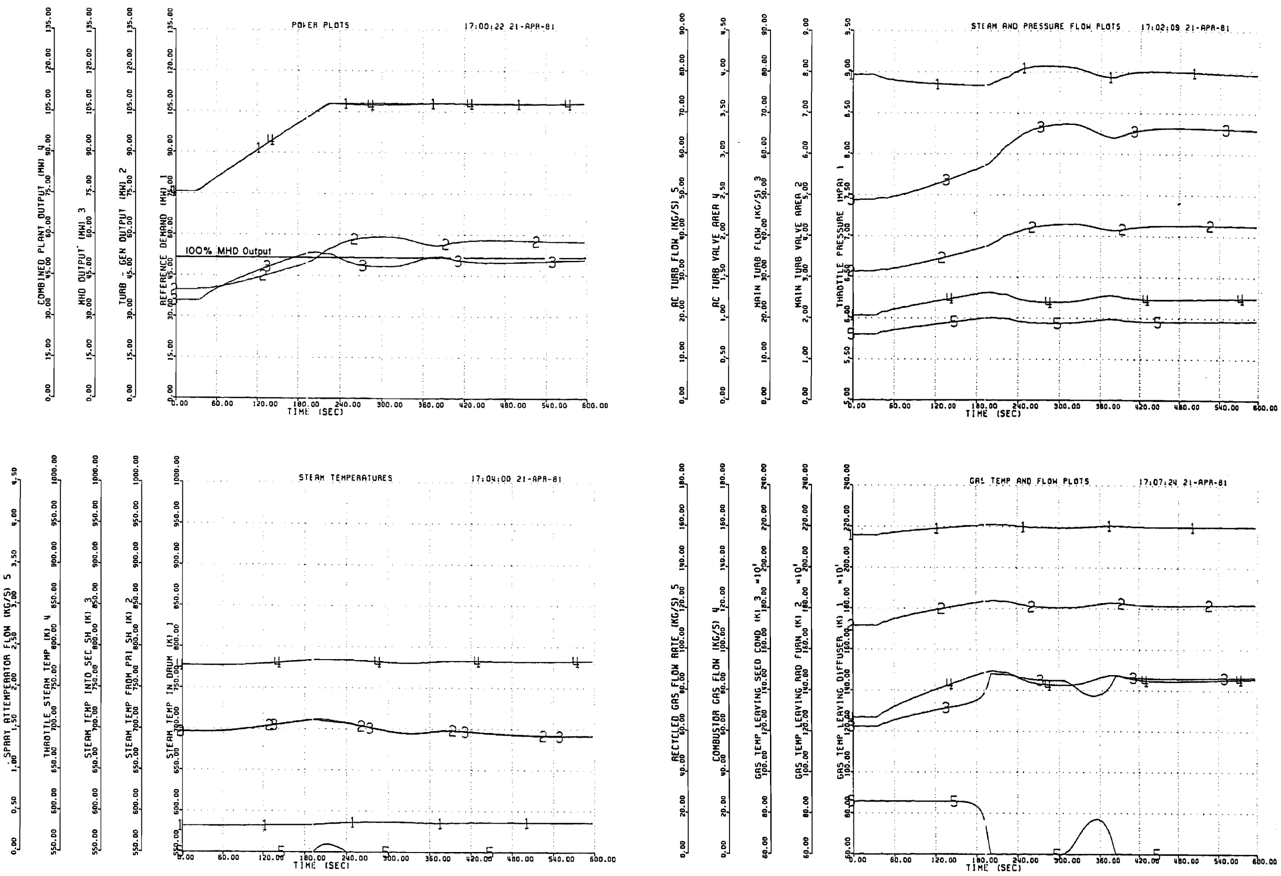

Figure 11. Fully Coordinated Control. No Channel Limiting. Steam Temperature Gas Recycle Control.

overshoot of MHD output to 117 percent (60.0 MW), with a long tail after ramp cessation, a typical response for such control. Throttle pressure shows a wedge-shaped depression, recovering without overshoot. Steam temperature is about 20K low at the outset, becoming well-controlled with the early onset of attemperator spray. Gas temperature is well-controlled.

Figures 13 and 14 are examples of MHD-following control, with no channel limiting and with 100 percent channel limiting. Excellent load tracking is seen in both cases, which is characteristic of MHD-following. Power plots give the appearance that hard channel limiting is a clear choice. However, behavior of main steam pressure belies this. It is evident that channel limiting at 100 percent causes a serious decline in throttle pressure. The decline occurs because hard limiting of channel output implies hard limiting of boiler firing, a condition that will not support the necessary transient behavior. Other simulations (not shown) indicate that a limit of 105 percent allows throttle pressure to survive the transient.

No examples with gas recycling are shown since their behaviors are quite similar to those shown above.

Figure 15 is an example of MHD-leading control with no channel limiting and no gas recycling. Relatively sluggish load tracking is seen, coupled with low MHD-channel overshoot of 106 percent (54.6 MW), and better controlled throttle pressure than in the corresponding MHD-following case. Slow, extremely stable response is typical of MHD-leading control. Gas recycling response (not shown) is again similar to that already seen.

V. Conclusions

A typical set of three conventionally-based control strategies for combined-cycle MHD-steam plants is shown. Responses of coordinated control and MHD-following control are similar, while MHD-leading control has a separate typifying appearance. Load-following characteristics of the first two strategies are demonstrated superior to that of MHD-leading. Combustion gas is recycled in two distinct modes, controlling main steam temperature or seed condenser exit gas temperature.

A choice of control satisfying the criteria of plant stability, load following, steam pressure

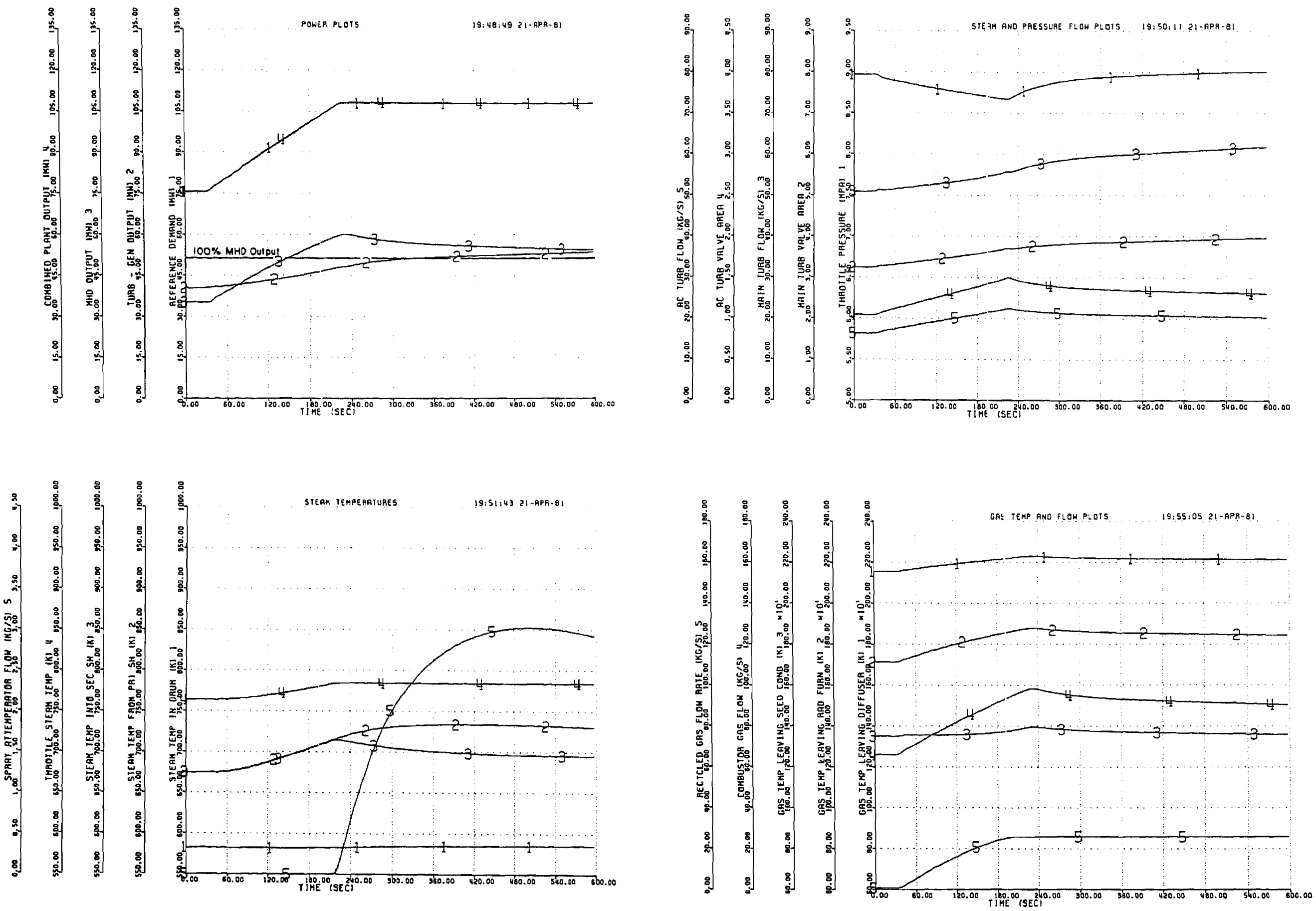

Figure 12. Fully Coordinated Control. No Channel Limiting. Gas Temperature Gas Recycle Control.

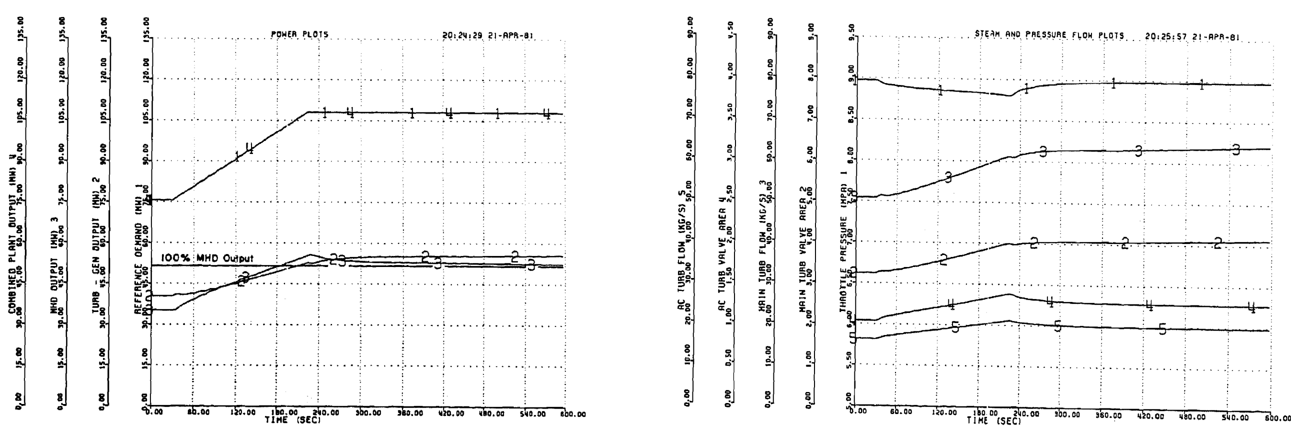

Figure 13. MHD-Following Control. No Channel Limiting. No Gas Recycling.

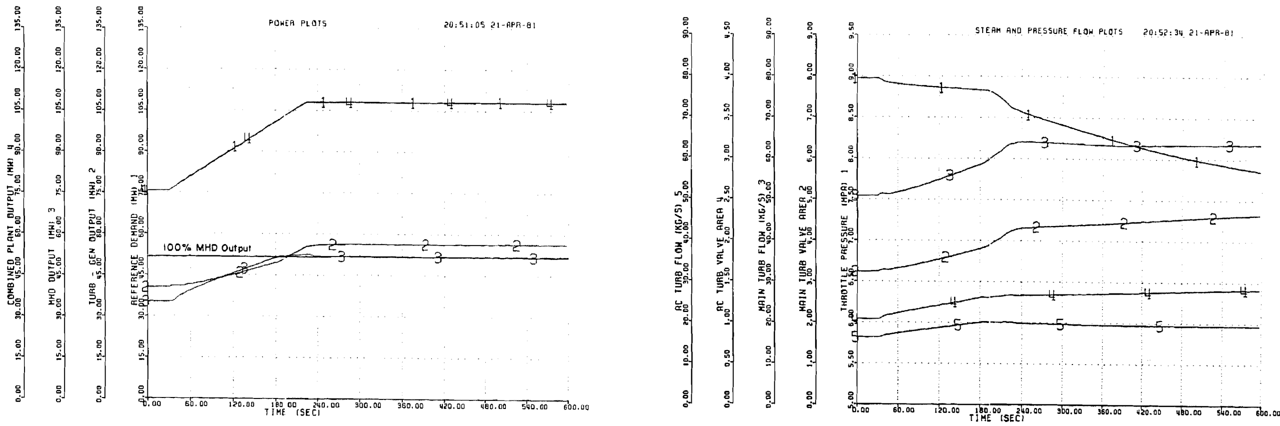

Figure 14. MHD-Following Control. Channel Limit at 100%. No Gas Recycling.

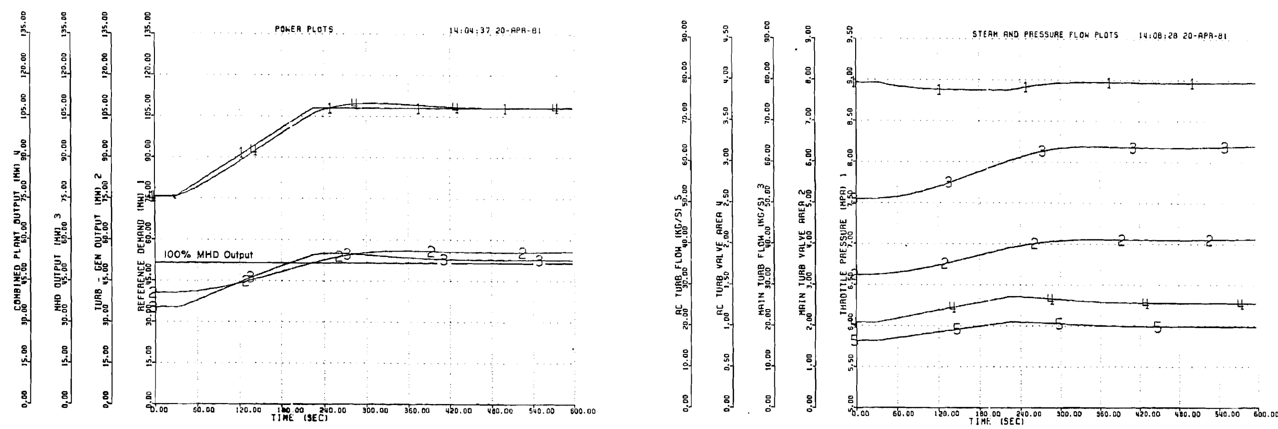

Figure 15. MHD-Leading Control. No Channel Limiting. No Gas Recycling.

regulation, and minimum channel overshoot would admit both coordinated control and MHD-following control, with steam temperature gas recycle control. The resultant seed condenser exit temperature profile may be poor from the viewpoint of the seed recovery process.

Further simulation (not shown) indicates that MHD-following is less stable than coordinated control. A certain looseness of main steam pressure must be tolerated by the air compressor controller. With an MHD-following strategy, values of K_{61} greater than 2.5 yield an unstable plant, whereas coordinated control is stable and well-behaved with such a value.

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