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SOLAR HYBRID PLANTS—POWER SYSTEM
INTERFACE ANALYSES

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Dynamic Thermal Modeling of Solar - Fossil Fuel Hybrid Plants

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ABSTRACT

A model is developed which yields the solar flux density distribution on the surface of a vertical cylindrical receiver mounted on a tower centrally located in a horizontal circular ring-shaped mirror field. The flux density at a given location on the receiver surface is shown to be given by the numerical integration of a simple analytical expression. Strategies are examined for redistributing the solar flux input to obtain a desired distribution or maintain a specified distribution throughout the day. The solar flux density distribution is expressed as a dimensionless concentration ratio which can be derived from universal curves and then used in the design of receivers to meet specified flux levels.

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1. Power System Control

1.1 Overall System Control

The overall control system for a large-scale electric power system is one of the most complex control systems in existence. It must function to match generation to load demand instant-by-instant in the face of continuously changing loads, all the while maintaining frequency to close tolerances, and maintaining a nearly distribution network.

Figure 1. Overall Generation Control of a Power System.

The overall control of generation in a designated power system control area (CA) is shown in Figure 1.

Each of the components of the overall system in figure 1 has its own model; these generally prove to be non-linear. Insofar as modeling solar-fossil fuel hybrid (SFFH) plants are concerned, the important portion is designated as boiler-turbine control in figure 1. In a modern power plant, the boiler and turbine controls operate in concert because their operating characteristics are interdependent. There is relatively little energy storage in the system and thus the combined control is necessary to provide the desired output under both transient and steady-state conditions.

1.2 Boiler-Turbine Control in Power Plants

Present-day power plants generally use an integrated control scheme for boiler-turbine control. In this scheme, the boiler firing rate, the boiler feedwater pumping rate, and the turbine throttle are simultaneously adjusted to follow load demand changes imposed on the generating unit. A block diagram showing the principle elements, and the measured and controlled quantities, of an integrated unit control system is shown in figure 2. ⁽¹⁾

A more detailed block diagram of an integrated boiler-turbine control system is given in figure 3. ⁽¹⁾ A control system as depicted in figure 3 allows rapid plant response to changes in load demand, yet minimizes deviations in boiler

temperature and pressure.

In considering a SFFH plant, there are obvious modifications necessary to figure 3 to accomodate the solar thermal input to the plant. It will be necessary to have separate control

Figure 2. Integrated Boiler-Turbine Control

of the solar thermal flux density at the receiver (via proper control of the heliostat field). These modifications are shown in figure 4, with the further details of figure 3 that remain unchanged being omitted.

The purpose of the boiler-turbine control system is to control the power output of the turbine, and to control the steam pressure, temperature, and enthalpy (BTU/lb.) output of

Figure 3. Control Function in an Integrated Boiler-Control Scheme.

the boiler. The necessary sensors, limiters, control methods, and actuators exist to control the process variables in fossil fuel power plants with a high degree of reliability; it is assumed that they could be used, with satisfactory performance, in a SFFH plant as well.

The fundamental model that is needed to study the thermal dynamics of a SFFH plant is a low-order model of the solar boiler and the fossil fuel boiler. Such a model will allow the determination of basic plant operating strategies and heliostat field control guidelines.

2. Low-Order Boiler Models

2.1 General Models

The firing system (heat source) and the steam generating

system can be represented as in figure 5. (2) Note that the steam system itself is a two input - two output representation in which each of the outputs depends on both of the inputs, as indicated by the dotted lines. The firing system can be represented by one or more time lags and perhaps a delay function. The steam system can be described by two equations:

$$W_T = F_1(s) W_V + F_2(s) X_{TV} \quad (2-1)$$

$$P_T = F_3(s) W_V - F_4(s) X_{TV} \quad (2-2)$$

Figure 4. Modifications to Control System for SFFH Plant.

In these equations, $F(s)$ indicates Laplace-transform notation, and the negative signum on $F_4(s)$ is because an increased throttle valve opening will result in a decrease in throttle pressure.

The steam system of figure 5 can be modeled as the analog two - port electrical network shown in figure 6.⁽¹⁾ In figure 6, the capacitances represent energy storage capability, the conductance G represents steam flow admittance that produces a pressure drop, current is analogous to flow rate, W , and voltage is analogous to pressure P . The describing equations for figure 6 are:

$$W_1 = (G + C_1 s) P_1 - G P_2 \quad (2-3)$$

$$-W_2 = -G P_1 + (G + C_2 s) P_2 \quad (2-4)$$

Figure 5. Firing System and Steam System.

By solving equations (2-3) and (2-4) for P_1 and P_2 in terms of the flow rates, it is possible to express output pressure as a function of the two flow rates as:

Figure 6. Two - port electrical analog of steam system.

$$P_2 = \frac{G}{s(GC_3 + C_4s)} W_1 - \frac{(G + C_1s)}{s(GC_3 + C_4s)} W_2 \quad (2-5)$$

$$\text{where } C_3 = C_1 + C_2$$

$$C_4 = C_1C_2$$

There are several boiler models that have been developed, whose describing equations can be put in the form of equation (2-5). Two of these are the Frensch and Klefenz model, and the Laubli and Fenton model.⁽²⁾ Both of these models utilize linear transfer functions throughout and can be used, with good results, for small disturbances. A third model, which should give more accurate results for large disturbances because

it more accurately models the non-linearity of certain processes, is the one proposed by an IEEE Working Group. ⁽³⁾

2.2 The IEEE Boiler Model

The IEEE boiler model, including the firing system, is given in figure 7. The IEEE model assumes that steam flow varies as the square root of the pressure drop through the boiler, and that W_T is the product of P_T and X_{TV} . The latter can be considered a gain adjustment such that the governor dictates energy withdrawal from the boiler.

In figure 7, W indicates mass flow rate of steam (kg/sec. or lb. - mass/sec.), and P indicates pressure (newtons/ m^2 or psi). The describing equations for the steam flow and pressure are:

$$P_D = \frac{1}{C_D s} [W_V - W_S] \quad (2-6)$$

$$P_T = \frac{1}{C_{SH} s} [W_S - W_T] \quad (2-7)$$

$$W_S = K \sqrt{P_D - P_T} \quad (2-8)$$

$$W_T = X_{TV} P_T \quad (2-9)$$

With respect to the time delay and time constants of the firing system in figure 7, the water wall time constant τ_w is in the range of 5 to 7 seconds. ⁽¹⁾ Typical values of τ_d and τ_F for different types of firing systems are given in figure 8. ⁽¹⁾

Figure 7. IEEE Firing System and Boiler Model

<u>Type of Firing System</u>	<u>τ_d, sec.</u>	<u>τ_F, sec.</u>
oil	0	2
pulverized coal with bunker	0	20
pulverized coal injection-fast	15	60
pulverized coal injection-slow	50	175
grate firing	60	200

Figure 8. Time Delays and Time Constants of Boiler Firing Systems.

The next step involves modification of the firing system and boiler model of figure 7 to include solar thermal input.

3. Thermal Models of Solar - Fossil Fuel Hybrid Plants

3.1 General

Figure 4 of section 1.2 shows a functional block diagram to control the process variable in a SFFH plant. In studying the thermal dynamics of a SFFH plant, it is necessary to modify a model such as the firing system and boiler model of figure 7. This immediately resolves itself into two categories - (1) A new SFFH plant that is originally designed and constructed to utilize both fossil fuel thermal energy and solar thermal energy, and (2) the case of retrofitting an existing fossil fuel plant to accept solar thermal input. Each of these are discussed in the following sections.

3.2 New Plant Designed as a Hybrid Plant

As a sub-contractor to the G.T. Sheldahl Co. under NSF grant number GI - 41019, the Foster Wheeler Corporation

investigated all possible methods of utilizing solar thermal input to a SFFH plant. Their preferred method consists of utilizing the solar thermal energy in an evaporator and superheater that operates in parallel with the fossil fuel evaporator and superheater. Their conceptual design for a tower - mounted, multi - pass, once-through boiler consists of an outer row of tubes for evaporation of water and an inner row of tubes for superheating of steam. Following the notation and schematic of figure 7, the combined solar and fossil fuel thermal inputs are illustrated in figure 9. A second subscript S indicates

Figure 9. Combined Solar and Fossil Fuel Thermal Model.

solar, and a second subscript F indicates fossil fuel.

In arriving at a transfer function model for the solar thermal input system that is consistent with that of figure 7, several assumptions and observations are necessary. These are:

- (1) It will be assumed that the heliostat field can be represented by a transfer factor, K_H , and a time constant τ_H .
- (2) It will be assumed that the evaporator and superheater can be represented by a transfer factor, K_E , and a thermal time constant, τ_E , insofar as energy transfer from solar thermal to steam enthalpy is concerned.
- (3) As in the IEEE boiler model, it will be assumed that steam flow varies as the square root of the pressure drop through the boiler, and that this effect is lumped across the superheater.
- (4) It will be assumed that there is a transport time delay τ_S associated with the flow of superheater steam from the tower-mounted boiler to the throttle valves of the steam turbine.

With these assumptions, the combined thermal model for a SFFH plant is shown in figure 10. Dashed lines indicate solar portions and solid lines indicate fossil fuel portions.

3.3 Model of a Retrofit Hybrid Plant

The difference between a SFFH plant that is a new plant designed as a hybrid plant from the outset and a SFFH plant that is the result of a retrofit of an existing plant lies in the boilers. In the case of a new plant, it would be possible

Fossil fuel
firing rate

solar
firing
rate

Figure 10. Combined Thermal Model for a SFFH plant.

to use a common feedwater heater and economizer as suggested by Foster Wheeler Corp. In the case of retrofit of an existing plant, these portions of the thermal cycle might be distinct for the fossil fuel part and the solar part. Nevertheless, the modeling of the important boiler functions, i.e., evaporation and superheater, would be the same as shown in figure 10. The only difference would be in the manner in which the plant control system is designed to control the major processes such as feedwater heating and superheat spray control.

4. Conclusions

A low-order thermal model is given for a SFFH plant. The various transfer constants and time constants will be needed to allow further study, and an appropriate steam turbine model can be added if steam turbine response is desired.⁽³⁾ The model should allow a determination of hybrid plant response characteristics when disturbances, such as moving shadows across the heliostat field, are present. More importantly, it may help to define important parameters, time delays, or certain operating limitations of SFFH plants.

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