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Decentralized Nonlinear Control of 300MWe Circulating Fluidized Boiler Power Unit

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Abstract **—The dynamics of large scale circulating fluidized bed (CFB) boiler power plant shows the behaves of large time delay, complex coupling and nonlinearities, which brings difficulties for controller design to improve the plant performance. This paper firstly introduces a well-established and validated nonlinear model of a 300MWe CFB power plant, and then the model is simplified through analysis and approximation which could show clearly the reason of difficulties associated with controller design. It is found that the coupling and nonlinearity mainly come from the opening of main steam governing valve under various load conditions, and it is hard to completely decouple the multivariable system. To avoid the difficulties of decoupling, a decentralized PID control system is finally proposed to control the unit power and main steam pressure after nonlinear model transformation. The simulation results show that the control system has improved dynamic performance in load reference tracking for a wide range of load changes, and also good disturbance rejection to the coal quality variation. The analysis and control in this paper provide the first step to move forward for future control quality improvement and advanced control strategy study.**

Keywords- CFB control; nonlinearity; decentralized control; PID controller

I. INTRODUCTION

As one of the promising clean coal utilization technologies, the circulating fluidized bed (CFB) boiler has gained rapid development in recent years [1]. Compared with traditional pulverized coal-fired (PC) power plant, CFB power plant offers the distinct advantages such as more fuel flexibility, lower pollution emission, wider operation range and higher combustion efficiency. Meanwhile, the wider operation range and complicated combustion process brings more nonlinearities into the unit dynamics. Since the heat release of coal combustion goes through repetitious circulating, the time delay and inertia from fuel disturbance of CFB boiler to the unit load fluctuation is much longer than those of PC power plants. And similar to the PC power plant, both of the fuel feed flow rate and governor valve position of steam turbine have prominent influences on the main steam pressure and unit power output simultaneously. Thus, the control of a CFB boiler power plant is a more challenging task than that of PC power plant, especially for its coordinated control system.

There are many advanced control strategies reported on the coordinated control of thermal power plants, such as active disturbance rejection control [2-3], nonlinear control based on approximate or exact feedback linearization [4-5], gain scheduling control [6], intelligent algorithm-based optimization control [7], etc. Most advanced control strategy simulation shows satisfactory control performance, but in fact it is hard to be implemented in the real power plant due to its complicated control design procedure or inconvenient tuning method. In addition, their applications to CFB power plants are rarely reported.

PID control is the most widely used control strategy in real control engineering of thermal power plants, usually merged with some amelioration elements such as unit load feed-forward compensations and nonlinear elements if necessary. In recent years, direct energy balance (DEB) control is very popular in coordinated control of thermal power plants in China. By integrating gain scheduling principle to eliminate the static gain nonlinearity [8], it can balance the turbine energy demand and boiler heat supply, and consequently improve the control performance under load variations. But the parameter tuning of DEB is of great dependence on engineers' experience and it is time-consuming to obtain final energy balance [2].

Since there is currently no well-accepted coordinate control strategy for CFB power plants, it is important to test any new control strategy in simulation using a full-scale verified nonlinear dynamic CFB power plant model before it can be implemented in practice. Some nonlinear models have been developed for CFB power plant in the last twenty years, and they are valuable in understanding the complex mechanisms of CFB process. However, those models have given very limited contributions to control system design or control engineering practice. The main reason may be that the modeling motivation is not for control study so that its dynamics has not been validated in the full load operation range to reveal the characteristic of nonlinearity, coupling, large time delay and high order inertia quantitatively. In addition, large scale CFB power plant has just accomplished its demonstration several

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years before, so its modeling and control problem is still under investigation.

In this paper, a well-established nonlinear model of 300MWe CFB power plant in [9] is introduced. The model was built up to facilitate the coordinated control field adjustment. After reasonable model structure selection and model parameters identification, the nonlinear model is validated by using various load operation data in a real 300MWe CFB power plant. Thus it can be used to explore the coordinated control design of large scale CFB power plants.

The organization of this paper is as follows. In section II, we give an introduction to the nonlinear model of CFB power plant. In section III, the nonlinearity of CFB model is analyzed, followed with model approximation and reconstruction. In Section IV, the decentralized nonlinear control system is designed, and simulation results are presented in Section V to show its control ability on load reference tracking and coal quality disturbance rejection. Finally, the conclusion is given in section VI.

II. A NONLINEAR MODEL OF 300 MWE CFB POWER UNIT

Based on a nonlinear boiler-turbine model structure proposed in [10], a nonlinear boiler-turbine unit model for a 300MWe CFB power plant is developed [9] in Simulink to facilitate field commissioning of coordinated control system. The model structure is shown in Fig.1, and Tab. 1 gives the symbol annotations.

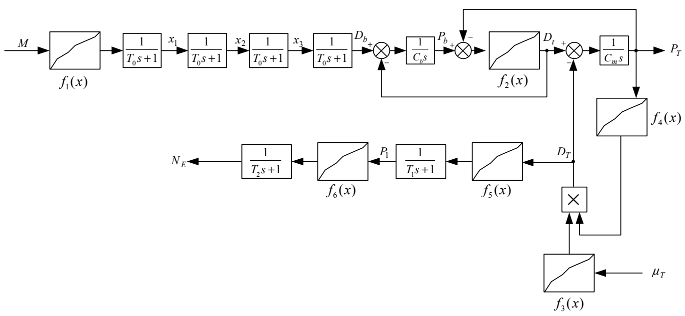

Figure 1. Nonlinear model structure of 300MWe CFB power plant

TABLE I. SYMBOL ANNOTATION

Symbol	Annotation
M	Fuel flow rate
μ_T	Opening of steam turbine governing valve
P_T	Main steam pressure
N_E	Generator output power
D_b	Heat produced in boiler
P_b	Drum pressure
D_t	Steam flow rate generated by boiler
D_T	Inlet steam flow rate of turbine
P_1	First stage pressure of turbine
T_0, T_1, T_2	Time constants
C_b	Heat storage coefficient
C_m	Volume storage coefficient
$f_i(x)$, $i=1,\cdots,6$	Nonlinear mapping functions
x_1, x_2, x_3	Intermediate state variables

In Fig.1, nonlinear mapping function $f_i(x), i=1,\cdots,6$ is used to depict the static gain nonlinearity with load condition changes. They are identified by using the full-scope operating data of a real 300MWe CFB power plant [9]. The time constants T_0, T_1, T_2 and coefficients C_b , C_m are also identified from operating data of the same power plant in transient processes. Their values can be found in Appendix Tab. II and III.

Denote the system state X and output variable Y as:

$$\begin{aligned} X &= [x_1, x_2, x_3, D_b, P_b, P_T, P_1, N_E]^{\mathrm{T}} \\ &= [x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8]^{\mathrm{T}} \end{aligned} , \tag{1}$$

$$Y = [P_T, N_E]^{\mathrm{T}} = [y_1, y_2]^{\mathrm{T}} , \tag{2}$$

then the CFB model shown in Fig. 1 can be expressed as follows:

$$\begin{cases} \dot{x}_1 = \dfrac{1}{T_0}[-x_1 + f_1(M)] \\ \dot{x}_2 = \dfrac{1}{T_0}(x_1 - x_2) \\ \dot{x}_3 = \dfrac{1}{T_0}(x_2 - x_3) \\ \dot{x}_4 = \dfrac{1}{T_0}(x_3 - x_4) \\ \dot{x}_5 = \dfrac{1}{C_b}[x_4 - f_2(x_5 - x_6)] \\ \dot{x}_6 = \dfrac{1}{C_m}[f_2(x_5 - x_6) - f_4(x_6)\cdot f_3(\mu_T)] \\ \dot{x}_7 = \dfrac{1}{T_1}[f_5(f_4(x_6)\cdot f_3(\mu_T)) - x_7] \\ \dot{x}_8 = \dfrac{1}{T_2}[f_6(x_7) - x_8] \end{cases} , \tag{3}$$

$$Y = [x_6, x_8]^{\mathrm{T}} \tag{4}$$

Obviously, it is a nonlinear model due to the involvement of six nonlinear gain functions $f_i(x), i=1,\cdots,6$.

To ensure that the power units can response quickly to grid load demand while maintaining the key parameters within their permitted limits, the coordinated system of a CFB boiler power plant should manipulate the control variable M and μ_T to meet the following specifications:

(1) For a variable load reference, the unit load should follow load reference closely, and the main steam pressure fluctuation should be as small as possible.

(2) For a fixed load reference, the internal disturbance from combustion system should have little influence on the main steam pressure and unit load.

III. MODEL APPROXIMATION

By plotting all the nonlinear mapping functions $f_i(x), i = 1,\cdots,6$, it is noticed that the nonlinearities associated with $f_i(x), i = 1,2,5,6$ are very close to linear relationship, so they can be linearized as:

$$f_i(x) \approx k_i x, i = 1,2,5,6\,, \tag{5}$$

where $k_i, i = 1,2,5,6$ are constant coefficients. In this way, the nonlinear model (3)(4) can be approximated as:

$$\dot{X} = \begin{bmatrix} -\frac{1}{T_0} & 0 & & \cdots & & & & 0 \\ \frac{1}{T_0} & -\frac{1}{T_0} & 0 & & & & & \\ 0 & \frac{1}{T_0} & -\frac{1}{T_0} & 0 & & & & \\ 0 & 0 & \frac{1}{T_0} & -\frac{1}{T_0} & 0 & & & \vdots \\ & & 0 & \frac{1}{C_b} & -\frac{k_2}{C_b} & \frac{k_2}{C_b} & & \\ \vdots & & & \ddots & \frac{k_2}{C_m} & -\frac{k_2}{C_m} & 0 & \\ & & & & 0 & 0 & -\frac{1}{T_1} & 0 \\ 0 & 0 & & \cdots & & 0 & \frac{k_6}{T_2} & -\frac{1}{T_2} \end{bmatrix} X + \begin{bmatrix} \frac{k_1 M}{T_0} \\ 0 \\ 0 \\ 0 \\ 0 \\ -\frac{f_4(x_6) f_3(\mu_T)}{C_m} \\ \frac{k_5}{T_1} f_4(x_6) f_3(\mu_T) \\ 0 \end{bmatrix} \tag{6}$$

$$Y = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} X\,. \tag{7}$$

The simplified model is still a nonlinear model, and now the nonlinearity mainly comes from $f_4(P_T) f_3(\mu_T)$, especially the opening of governor valve μ_T for the fixed pressure operation.

We select a new control input D_T instead of μ_T as:

$$D_T = f_4(x_3) f_3(\mu_T)\,, \tag{8}$$

and substitute (8) into (6), then we have

$$\dot{X} = \begin{bmatrix} -\frac{1}{T_0} & 0 & & \cdots & & & & 0 \\ \frac{1}{T_0} & -\frac{1}{T_0} & 0 & & & & & \\ 0 & \frac{1}{T_0} & -\frac{1}{T_0} & 0 & & & & \\ 0 & 0 & \frac{1}{T_0} & -\frac{1}{T_0} & 0 & & & \vdots \\ & & 0 & \frac{1}{C_b} & -\frac{k_2}{C_b} & \frac{k_2}{C_b} & & \\ \vdots & & & \ddots & \frac{k_2}{C_m} & -\frac{k_2}{C_m} & 0 & \\ & & & & 0 & 0 & -\frac{1}{T_1} & 0 \\ 0 & 0 & & \cdots & & 0 & \frac{k_6}{T_2} & -\frac{1}{T_2} \end{bmatrix} X + \begin{bmatrix} \frac{k_1 M}{T_0} \\ 0 \\ 0 \\ 0 \\ 0 \\ -\frac{D_T}{C_m} \\ \frac{k_5}{T_1} D_T \\ 0 \end{bmatrix}. \tag{9}$$

Thus the nonlinear model (6)(7) can be rewritten in a linear state space representation as follows:

$$\begin{cases} X = AX + BU \\ Y = CX \end{cases}, \tag{10}$$

where,

$$A = \begin{bmatrix} -\frac{1}{T_0} & 0 & 0 & & \cdots & & 0 & 0 \\ \frac{1}{T_0} & -\frac{1}{T_0} & 0 & & & & & 0 \\ 0 & \frac{1}{T_0} & -\frac{1}{T_0} & 0 & & & & \\ 0 & 0 & \frac{1}{T_0} & -\frac{1}{T_0} & 0 & & & \vdots \\ & & 0 & \frac{1}{C_b} & -\frac{k_2}{C_b} & \frac{k_2}{C_b} & & \\ \vdots & & & \ddots & \frac{k_2}{C_m} & -\frac{k_2}{C_m} & 0 & 0 \\ & & & & 0 & 0 & -\frac{1}{T_1} & 0 \\ 0 & 0 & & \cdots & & 0 & \frac{k_6}{T_2} & -\frac{1}{T_2} \end{bmatrix} \tag{11}$$

$$B = \begin{bmatrix} \frac{k_1}{T_0} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{C_m} & \frac{k_5}{T_1} & 0 \end{bmatrix}^{\mathrm{T}} \tag{12}$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{13}$$

$$U = \begin{bmatrix} M & D_T \end{bmatrix}^{\mathrm{T}} \tag{14}$$

IV. CONTROL SYSTEM DESIGN

Both of the controllability matrix and observability matrix of system (10-14) have full rank, so the system is completely controllable and observable, a full-state feedback controller can be designed to move the initial states to any specified condition in a finite time interval without considering input constraints. Considering the motivation of control system implementation in the real CFB power plants, only PID controllers are adopted in this paper instead.

For linear system (10-14), a two-input-two-output transfer matrix can be derived as follows:

$$\begin{bmatrix} P_T(s) \\ N_E(s) \end{bmatrix} = \begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix} \begin{bmatrix} M(s) \\ D_T(s) \end{bmatrix} \quad (15)$$

where,

$$\begin{aligned} g_{11}(s) &= \frac{k_1 k_2}{s(1+T_0 s)^4 (C_m C_b s + k_2 C_m + k_2 C_b)} \\ g_{12}(s) &= \frac{-(C_b s + k_2)}{s(C_m C_b s + k_2 C_m + k_2 C_b)} \\ g_{21}(s) &= 0 \\ g_{22}(s) &= \frac{k_5 k_6}{(1+T_1 s)(1+T_2 s)} \end{aligned} \quad (16)$$

It has a half-decoupled structure, so a local controller can be tuned separately for the second loop $g_{22}(s)$. Here a PID controller is employed for the sake of simplification:

$$c_2(s) = \frac{k_{p2}}{k_5 k_6} \frac{(1+T_1 s)(1+T_2 s)}{s(1+T_2 s / T_f)}, \quad (17)$$

so that the open-loop transfer function of second loop approximates as

$$g_{2o}(s) = g_{22}(s) c_2(s) \approx \frac{k_{p2}}{s} \quad (18)$$

For the first loop, it is hard to compensate completely the disturbance from D_T to P_T owning to the realization difficulty of decoupling transfer function as well as input constraints. An approximately decoupling controller, such as P or PD controller can be designed to obtain partly decoupling if necessary. Here, a PI controller is designed for the first loop to explore the ability of decentralized control structure:

$$c_1(s) = k_{p1} + \frac{k_{i1}}{s}, \quad (19)$$

The above two controller parameters are tuned as:

$$k_{p1} = 50,\ k_{i1} = 0.1,\ k_{p2} = 1,\ T_f = 10. \quad (20)$$

The closed-loop control structure of CFB coordinated control system is shown in Fig. 2. Since the first loop output P_T is used to derive the second loop control action μ_T, so it is actually a partial decoupled control system even if it is represented in a simple decentralized structure.

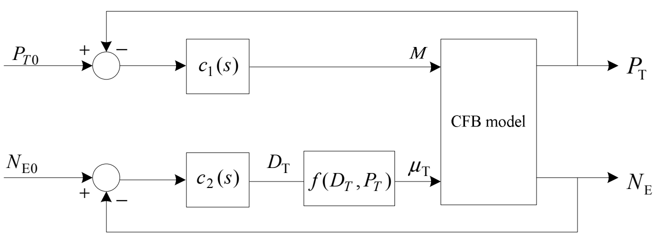

Figure 2. Control structure of CFB unit control

From the nonlinear mapping functions in Appendix, it is clear that nonlinear function $f_3(x), f_4(x)$ are both monotone increasing functions with constraints, their inverse functions exist in region of interest. Then it is realizable to derive the real control action μ_T from D_T and P_T as follows:

$$\mu_T = f(D_T, P_T) = f_3^{-1}[D_T / f_4(P_T)] \quad (21)$$

V. SIMULATION RESULTS

A. Change load reference

Starting close-loop simulation from 210 MWe (70% load), at 1000 s the load reference increases to 250 MWe with a rate of 0.3 MWe/s, and at 5000 s the load reference decreases to 170 MWe with a rate of 0.3 MWe/s. The dynamic responses of power output and main steam pressure are shown in Fig. 3(a)-(b). It can be found that the load output can rapidly follow its reference closely, while keeps the disturbance on main steam pressure within a small range of ±1 MPa. The dynamics of fuel flow rate and valve opening are also given in Fig. 3(c)-(d), they behave relatively smooth.

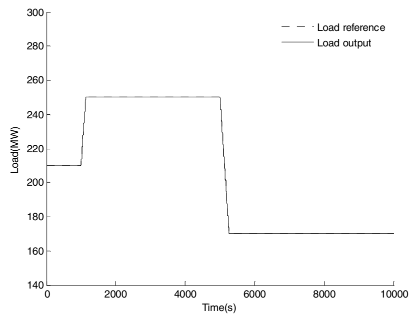

Figure 3(a) Load output response

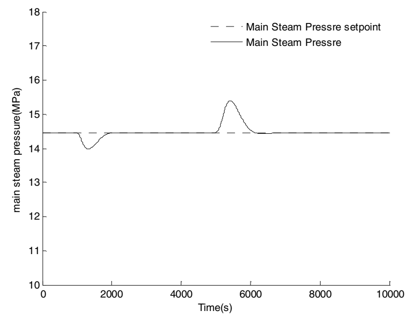

Figure 3(b) Main steam pressure response

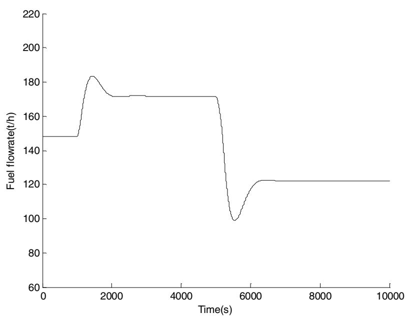

Figure 3(c) Fuel Flow rate response

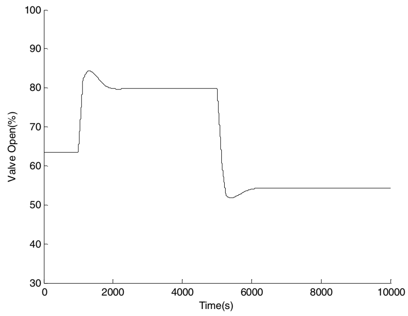

Figure 3(d) Valve Opening response

A simulation of larger load reference change is conducted, which is not shown in this paper for length limits. The simulation results indicates that the coordinated control system shows similarly good load following capacity without retuning the controller parameters for the situation that the manipulation of fuel flow rate and valve opening do not reach their limits.

B. Dynamics at fuel flow rate disturbances

The coal quality variation will influence the operation of power plant greatly by bringing uncertainty to control system. Here, the coal quality variation is treated as a fuel flow rate disturbance. Firstly a step fuel flow rate disturbance of -50 t/h at 1000 s is conducted, then followed with a step fuel flow rate disturbance of 100 t/h at 5000 s, Figure 4(a)-(d) illustrate the dynamic responses of unit load, main steam pressure, fuel flow rate and valve opening.

It is obviously that the coal quality disturbance has no influence on load output owning to the rapid opposite direction manipulation of valve opening. Since the disturbance is added directly to the fuel flow rate, the main steam pressure shows obvious departure from setpoint value and has a positive correlation with the amplitude of fuel flow rate disturbance.

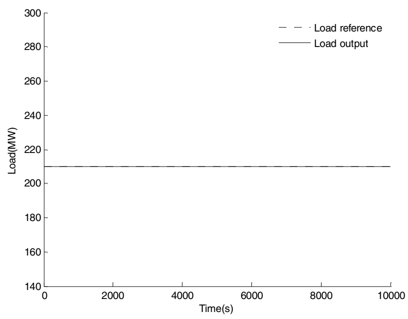

Figure 4(a) Load response at fuel flow disturbance

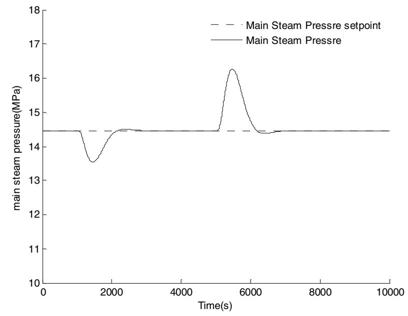

Figure 4(b) Main steam pressure response at fuel flow disturbance

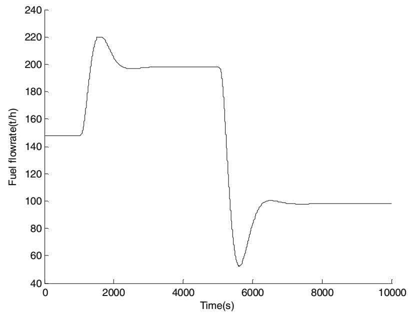

Figure 4(c) Fuel Flow disturbance

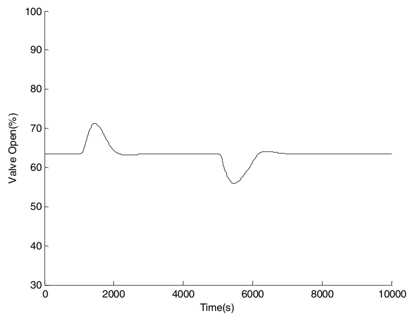

Figure 4(d) Valve Opening at fuel flow disturbance

VI. CONCLUSION

In this paper, a well-established and validated nonlinear model of a 300MWe CFB power plant is introduced and analyzed to reveal its control difficulty. It is found that the nonlinearity firstly comes from static gain changing with load, then from the opening of steam turbine governing valve. After some model approximation, it is still hard to fully decouple the two-input-two-output system. Then a decentralized PID control is designed to control the unit load and the main steam pressure by defining a new control variable and transforming the nonlinear model into a linear formula. Simulation results show that the control system has good performance in load reference tracking for a wide load change in operation conditions, and also good disturbance rejection for the coal quality variation. The analysis and control in this paper is the first step to move forward for future control quality improvement and advanced control strategy study.

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APPENDIX I

TABLE II. NONLINEAR MAPPING FUNCTION PARAMETERS FOR A 300MWE CFB MODEL[9]

Function	Parameter	Value										
$f_1(x)$	M(t/h)	0	40	60	80	100	120	140	160	180	200	220
	D_b(t/h)	0	127.3	202.9	295.8	405.5	496.1	583.2	664.3	763.6	858.4	915.1
$f_2(x)$	$P_b - P_T$(MPa)	0	0.15	0.3	0.45	0.6	0.75	0.9	1.05	1.2	1.35	1.5
	D_t(t/h)	0	160.7	280.4	410.1	509.4	578.5	641.1	720.1	796.3	859.7	907.5
$f_3(x)$	μ_T(%)	0	30	60	82	90						
	y	0	0.2	0.9	1.12	1.2						
$f_4(x)$	P_T(MPa)	0	3.4	5.1	6.8	8.5	10.2	11.9	13.6	15.3	17	
	D_T(t/h)	0	285.3	340.0	394.2	446.9	495.2	544.6	610.8	705.13	811.6	
$f_5(x)$	D_T(t/h)	0	50	150	250	350	450	550	650	750	850	1000
	P_1(MPa)	0	0.508	1.805	3.093	4.461	5.93	7.273	8.617	9.945	11.28	12.815
$f_6(x)$	P_1(MPa)	0	2.0	3.0	4.5	6.0	7.0	8.5	10.0	11.5	13.0	
	N_E(MW)	0	38.1	66.3	107.9	151.3	179.8	218.9	261.9	300.4	328.4	

TABLE III. TIME CONSTANTS AND COEFFICENTS OF A 300MWE CFB MODEL[9]

Parameter	T_0	T_1,	T_2	C_b	C_m
Value	23.57	1.77	0.75	35726.1	14101.5