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Multi-Objective Optimization for Active Disturbance Rejection Control for the ALSTOM Benchmark Problem

Chun'e Huang*, Zhongli Liu

The College of Biochemical Engineering, Beijing Union University, Beijing, China
Email: *hce137@163.com, *hchune@buu.edu.cn

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Abstract

Based on a thing that it is difficult to choose the parameters of active disturbance rejection control for the non-linear ALSTOM gasifier, multi-objective optimization algorithm is applied in the choose of parameters. Simulation results show that performance tests in load change and coal quality change achieve better dynamic responses and larger scales of rejecting coal quality disturbances. The study provides an alternative to choose parameters for other control schemes of the ALSTOM gasifier.

Keywords

Gasification, Multi-Objective Optimization, Non-Dominated Sorting Algorithm II (NSGA-II), Active Disturbance Rejection Control (ADRC)

1. Introduction

Integrated gasification combined cycle (IGCC) power plants are being developed to provide environmentally clean and efficient power from coal. GEC ALSTOM developed a small-scale prototype integrated plant, based on air-blown gasification cycle (ABGC). The gasifier as a component of the ABGC is a highly coupled multi-variable system with five inputs and four outputs and is found to be particularly difficult to control.

In 1997, the ALSTOM Energy Technology Center issued an open challenge to the UK Academic Control Community to develop advanced control techniques for the linear model of the ALSTOM gasifier. The "challenge information pack" [1] comprises three linear models with detailed specifications, including output limits, control input constraints, and disturbance tests. In June 2002, the second round challenge [2] [3] was issued, and

*Corresponding author.

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it extended the original study by providing the full non-linear model of the gasifier in M ATLAB/S IMULINK. Moreover, an expanded specification, which incorporates set point changes and coal quality disturbance, and a PI control strategy (also called the baseline control) introduced by Asmar [4] is included. More details of the gasifier can be found in [2] [3].

Many advanced control approaches have been applied in the control of the non-linear ALSTOM gasifier, such as H_2 methodology [5], H_∞ control [6], PID control [7], predictive control [8], proportional-integral-plus (PIP) [9], state estimation-based control [10], PI control [4] [11] [12], partially decentralized control [13], and so on. Although the performance tests of some advanced control methods are satisfactory, the multi-variable control structure is so complex that it is not easy to implement in practice. Among the control of the non-linear ALSTOM gasifier, the PI control shows obvious advantages because of their simple structure and better response performance. Recently, the active disturbance rejection control (ADRC) scheme proposed by Huang [14] achieved better performances than the PI control. However, the tuning of the parameters is still a difficult thing.

The non-dominated sorting genetic algorithm-II (NSGA-II) [15] is one of multi-objective evolutionary algorithms. Although many multi-objective evolutionary algorithms have been emerged, NSGA-II has attracted more and more attention for its fast non-dominated sorting, parameterless niching and elitist-preserving.

In the paper, based on the analysis of multi-objective optimal algorithm, NSGA-II is applied in the choice of parameters for ADRC schemes of the ALSTOM gasifier. Simulation results show that performance tests in load change and coal quality change achieve better dynamic responses and larger scales of rejecting coal quality disturbances. The content is arranged as follows: Section 2, ALSTOM gasifier model and control system specification are introduced; Section 3, NSGA-II for ADRC scheme of the ALSTOM gasifier is proposed, including the chose of objective function of multi-objective optimization, the results of the optimization and the performance tests; conclusion is given in Section 4.

2. ALSTOM Gasifier Model and Control System Specification

The gasifier is a non-linear, multi-variable component, and provided in the Challenge II of ALSTOM gasifier benchmark problem [3]. It is a reactor in which pulverized coal mixed with limestone, is conveyed by pressurized air into the gasifier, and gasified with air and injected steam, producing a low calorific-value fuel gas. The remaining char is removed from the base of the gasifier. The gasifier has five controllable inputs (coal, limestone, air, steam and char extraction) and four outputs (pressure, temperature, bed-mass and gas quality). In whole process, limestone is used to absorb sulphur in the coal, its flow rate must be set to a fixed ratio of coal flow, nominally 1:10 limestone to coal. This leaves a four-input four-output problem for the control design [1]. By the physical properties of the actuator devices, the non-linear gasifier model includes the input actuator flow limits and the rate of change limits, and the output limits, see [2] for details.

The control specification of the non-linear gasifier are listed as follows.

1) *Pressure disturbance tests*: A downstream pressure disturbance Psink, choosing from step disturbance of −0.2 bar or sine wave disturbance of amplitude 0.2 bar and frequency of 0.04 Hz, is applied to the gasifier, running the simulation 300 seconds; and calculate IAE index for the gas quality Cvgas and gas pressure Pgas over the complete run.

2) *Load change tests*: Start the system at 50% load in steady state and ramp it to 100% over a period of 600 seconds (5% per minute). The measured load should follow the load demand as closely as possible with minimal over shoot at the end of the ramp. The input constraints need to be adhered to the controller outputs all the time.

3) *Coal variation test*: Coal quality can change quite significantly depending on its source. It should be changed incrementally within the range ±18%, and any effect on the performance of the controller should be noted.

3. NSGA-II for ADRC Scheme of the ALSTOM Gasifier

In the control of the ALSOTM gasifier, the intension is that the performance tests would facilitate the evaluation of the closed-loop systems response to pressure disturbances, load changes and coal quality changes [2]. ADRC scheme of the ALSTOM gasifier was introduced by Huang [14]. In this case, the matching of the gasifier is listed as follows: gas calorific value with air flow, gas pressure with steam flow, gas temperature with char flow, and bed mass with coal flow, a feedforward and a proportional controller, three first-order active disturbance rejection controllers are designed to replace PI controllers in the baseline control. Thus, three ADRC controllers have four tuning parameters each, plus one parameter for the proportional control of bed mass and one for the feedforward gain to the coal flow (from char flow). More details can be found in original study [14].

In ADRC scheme, the parameter b_0 of each ADRC can be estimated based on the linear model in the first "Challenge Information Pack" [1], the value Tg_b_0, CV_b_0, and Pg_b_0 are listed as follows [14]:

$$Tg\_b_0 = 58.7822,\ CV\_b_0 = -8.2078\times10^5,\ Pg\_b_0 = 4.9596\times10^5.$$

Moreover, the adding of ADRC gives rise to the order increase of the gasifier, the initial states $x0c$ should be reset, and the initial values $u0$ of each ADRC can be initialized. The initial values $x0c$ and $u0$ at three loads can be obtained using the suggested method [14], as shown in **Table 1**.

3.1. The Formulation of Multi-Objective Optimization

In ADRC scheme, the parameter b_0 in each active disturbance rejection controller is fixed, there are three parameters β_1, β_2 and k_p. Hence there are eleven parameters which needed to be adjusted. The optimized variable X is represented as

$$\begin{aligned} X = \big(&Tgas\_k_p, Tgas\_\beta_1, Tgas\_\beta_2, Pgas\_k_p, Pgas\_\beta_1, Pgas\_\beta_2,\\ &CVgas\_k_p, CVgas\_\beta_1, CVgas\_\beta_2, Mass\_k_p, Mass\_k_f\big). \end{aligned} \tag{1}$$

The objective function is formulated as follows

$$\begin{aligned}
&f(X) = \left[f_{11}(X), f_{12}(X), f_{21}(X), f_{22}(X), \cdots, f_{61}(X), f_{62}(X),\right]\\
&f_{m1}(X) = f_{IAEm1}(X)\times10^{N_1+N_2},\\
&f_{m2}(X) = f_{IAEm2}(X)\times10^{N_1+N_2},\\
&f_{IAEm1}(X) = \int_0^\infty \left|\frac{y_{m1}(t)-y_{m1}^0}{y_{m1}^d}\right| \mathrm{d}t,\\
&f_{IAEm2}(X) = \int_0^\infty \left|\frac{y_{m2}(t)-y_{m2}^0}{y_{m2}^d}\right| \mathrm{d}t, m = 1,2,\cdots,6,\\
&N_1 = length\big(find\left(g_i(X) > 1\right)\big), i = 1,2,\cdots,6,\\
&N_2 = length\big(find\left(h_j(X) > 0.01\right)\big), j = 1,2,3,\\
&g_i(X) = \max\left|\frac{y_i - y_i^0}{y_i^d}\right|, i = 1,2,3,4,\\
&h_j(X) = \sum_{i=1}^{4}\max\left|\frac{y_i - y_i^0}{scale(i)}\right|, j = 1,2,3,\\
&scale(i) = \left[1e6 \quad 1e3 \quad 1e5 \quad 1\right].
\end{aligned} \tag{2}$$

where m $m(m = 1,2,\cdots,6)$ represent sequentially sine and step pressure disturbances at 100%, 50% and 0% loads; f_{m1} and f_{m2} represent RIAE indices of CVgas and Pgas in each scenario, respectively; N_1 and N_2 represent the numbers of going beyond outputs limits in all scenarios and the overshoot 1% at three loads,

Table 1. Initial value $x0c$ and $u0$ of ADRC scheme at three loads.

Load (%)	$x0c$	$u0$
100	$\left[x0c'\ 1221.6017\ 0\ 4.3584\times10^6\ 0\ 2\times10^6\ 0\right]'$	[0.9779 17.4391 2.6672 8.6123]
50	$\left[x0c'\ 1159.5945\ 0\ 4.472\times10^6\ 0\ 1.5711\times10^6\ 0\right]'$	[1.1873 12.1251 2.0071 6.8439]
0	$\left[x0c'\ 1066.3833\ 0\ 4.6871\times10^6\ 0\ 1.1469\times10^6\ 0\right]'$	[1.5519 6.5583 1.2367 5.1573]

respectively; y_{m1}, y_{m1}^{0} and y_{m1}^{d} represent the output, the equilibrium point data and the allowed fluctuation scope of the CVgas, respectively; y_{m2}, y_{m2}^{0} and y_{m2}^{d} represent the output, the equilibrium point data and the allowed fluctuation scope of the Pgas, respectively.

An index of coal quality flexibility was defined as follows [12]:

$$J_{CQ} = \sum_{m=1}^{6}\left(CQ_{\text{upper}}^{m} - CQ_{\text{lower}}^{m}\right), \tag{3}$$

CQ_{upper}^{m} and CQ_{lower}^{m} represent upper and lower limits of coal quality change percentage at scenario m when the inputs and outputs limits are guaranteed, respectively. The index J_{CQ} of each parameter set was calculated after running the simulation 40,000 seconds, then the optimal solution based on the biggest J_{CQ} value was chosen.

3.2. Results of Multi-Objective Optimization for the ALSTOM Gasifier

After multi-objective optimal algorithm has been run six times, a set of parameters are obtained, as shown in **Figures 1(a)-(d)**. **Figure 1(e)** and **Figure 1(f)** show the change of f_{IAEm1} and f_{IAEm2} in each scenario, respectively.

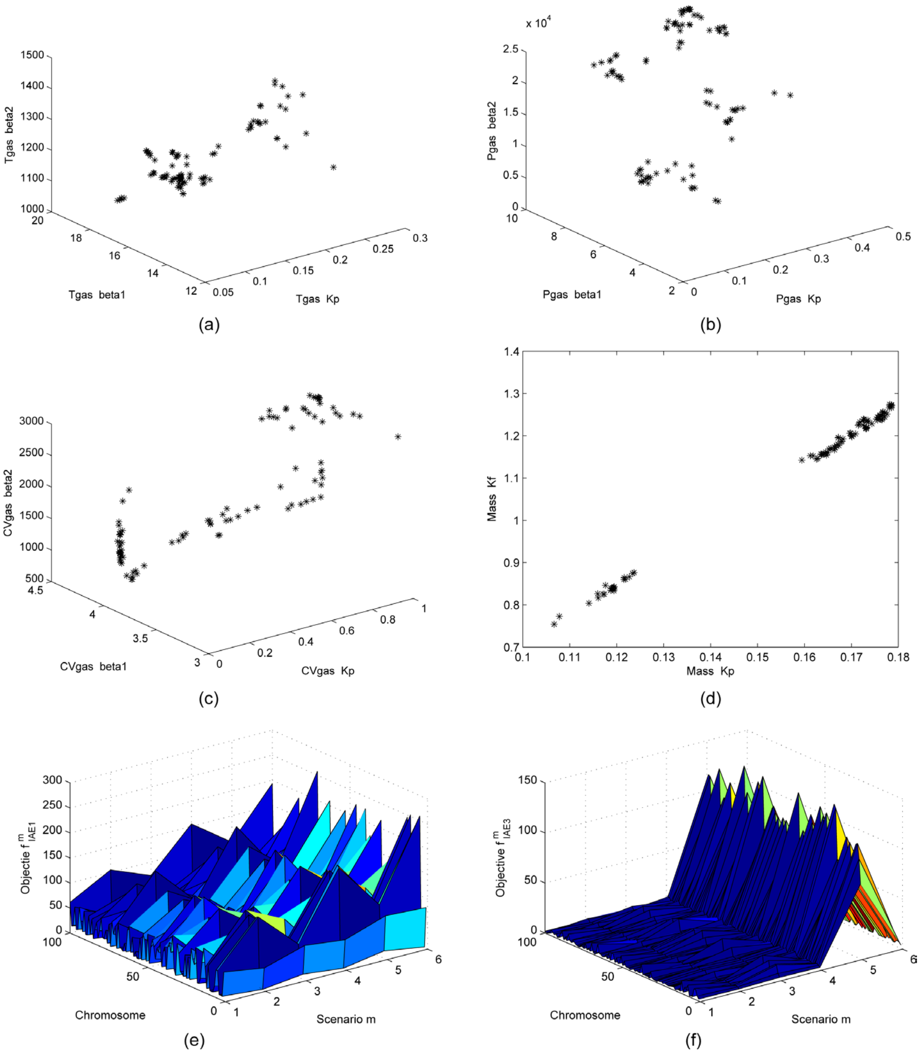


Figure 1. The optimal results of NSGA-II for ADRC scheme. (a) The ADRC parameters in Tgas loop; (b) the ADRC parameters in Pgas loop; (c) the ADRC parameters in CVgas loop; (d) the ADRC parameters in Mass loop; (e) the values f_{IAEm1} in each scenario; (f) the values f_{IAEm2} in each scenario.

Although the scope of the Y-axis the change of the RIAE indices of the CVgas in **Figure 1(e)** is irregular. The values f_{IAEm2} arrive at their biggest values in the fifth scenario corresponding to add sine disturbance to the gasifier at 0% load. The solution with the biggest the coal quality flexibility J_{CQ} is selected and shown in **Table 2** as MOADRC, where ADRC2 is the parameters obtained in [14].

The comparisons of the twelve objective functions and the total RIAE indices among Simm, ADRC2 and MOADRC are listed in **Table 3** and **Table 4**, respectively. **Table 3** and **Table 4** show that the values of the objective functions and the total RIAE indices of the ADRC2 and MOADRC are superior to the that of Simm's.

3.3. Performance Tests

With the parameter set MOADRC, the performance tests of ADRC scheme are done. The simulation results are compared with that of Simm's, MOPI2 and ADRC2.

Performance Tests

(1) *Psink disturbance tests*

Based on the specification of the ALSTOM gasifier [2], when the sine and step disturbances are added to the gasifier, respectively, the change of the corresponding indices are observed. All results of pressure disturbances can satisfy the requirements of the performance tests. **Figure 2** and **Figure 3** show the response graphs with step

Table 2. Comparison the ADRC2 with MOADRC.

Parameter	ADRC2	MOADRC	Parameter	ADRC2	MOADRC
Tg_k_p	0.1230	0.2063	Pg_k_p	0.2219	0.2625
Tg_β_1	7	14.3158	Pg_β_1	3	6.8761
Tg_β_2	1000	1263.9	Pg_β_2	20000	3311.5
CV_k_p	0.5610	0.9659	BM_k_p	0.1451	0.1234
CV_β_1	4	3.9855	BM_k_i	1.0328	0.8745
CV_β_2	2500	2798.8			

Table 3. Comparisons objective functions among Simm, ADRC2 and MOADRC.

Parameters	f_1	f_2	f_3	f_4	f_5	f_6
Simm	45.3820	74.6000	2.2312	6.72830	50.9100	91.8738
ADRC2	13.3933	0.9332	1.4512	2.9229	16.8375	1.2458
MOADRC	9.7081	13.5120	0.9806	2.3448	11.8789	18.1098
Parameters	f_7	f_8	f_9	f_{10}	f_{12}	f_{12}
Simm	2.4316	8.3613	64.5670	144.7509	3.1002	8.7586
ADRC2	1.9920	3.4737	24.8631	78.0664	2.9219	4.9765
MOADRC	1.0219	2.8156	16.8697	96.7032	1.0620	4.1163

Table 4. Comparisons sum of RIAE among Simm, ADRC2 and MOADRC.

Parameter	100%		50%		0%	
	sine	step	sine	step	sine	step
Simm	170.3016	46.4952	198.0433	45.4174	275.4846	46.4952
ADRC2	71.2025	14.9918	87.9738	15.4060	204.0164	21.7982
MOADRC	97.2771	15.6089	118.9365	15.7798	228.4470	21.7876

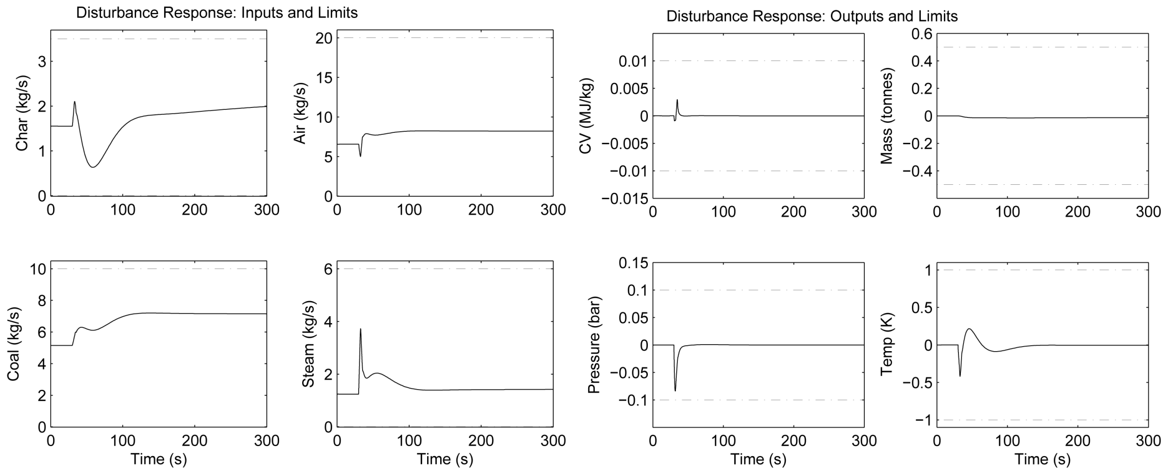


Figure 2. Response to step disturbance at 0% load.

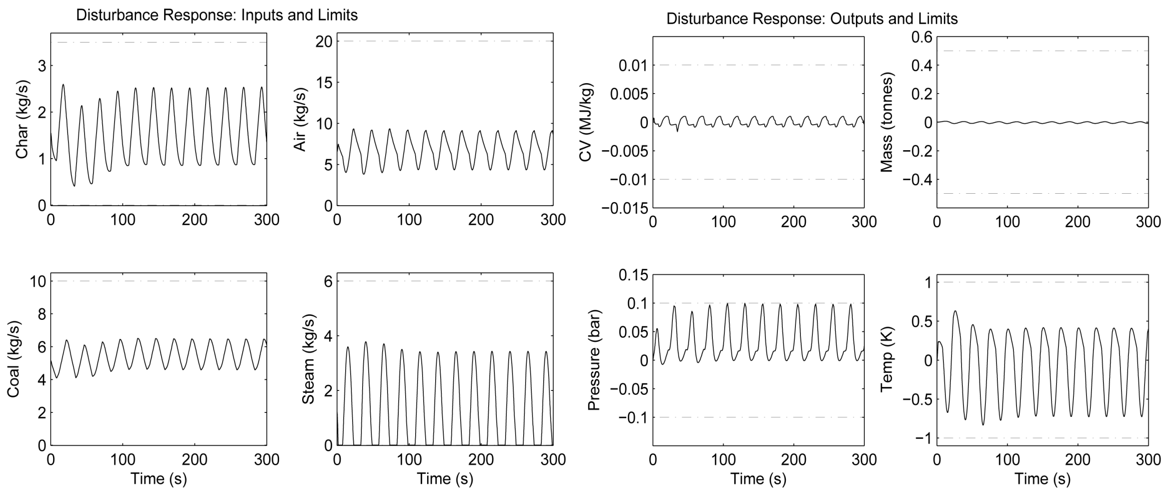


Figure 3. Response to sine disturbance at 0% load.

and sine disturbances at 0% load. The simulation results at 100% and 50% loads are omitted.

(2) *Load change test*

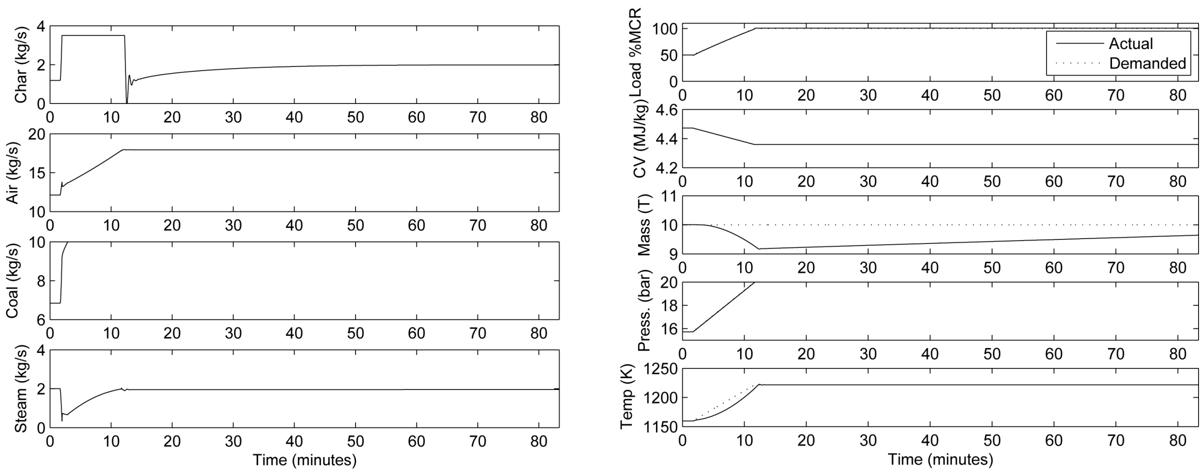
Load change test of MOADRC are shown in **Figure 4**, the comparisons of simulation results obtained from the four sets of parameters are shown in **Table 5**. The simulation results of the ADRC2 and MOADRC in **Table 5** show that the output temperature has almost no overshoot, and that the values of BM_min, BM_end and TPV_coal have a slight difference.

(3) *Coal quality change test*

In this test, when the coal quality is changed incrementally (within the range ±18%) with step or sine disturbance at certain load, upper and lower boundary guaranteeing the gasifier in steady state are recorded. The simulation results are shown in **Table 6**. The coal quality flexibility J_{CQ} based on the formula (3) are calculated and shown in **Table 7**. The parameter set MOADRC have the biggest coal quality flexibility than other parameter families.

4. Conclusion

In this study, NSGA-II is introduced to choose the set of control parameters for ADRC scheme of the ALSTOM gasifier. Simulation results with the optimized parameters show that load change and coal quality change achieve relative good dynamics responses, larger scales of rejecting coal quality disturbances. The study also provides an alternative to choose parameters for other control schemes of the ALSTOM gasifier.



(a) (b)

Figure 4. Response to the load change test. (a) Inputs response to load change; (b) outputs response to load change.

Table 5. Comparisons of the indices in load change test.

Index	Ch_min	T_max	BM_min	BM_end	TPV_coal
Unit	(kg)	(K)	(kg)	(kg)	(s)
Simm	0	1226.1	9096.4	9629.0	118.7
MOPI2	0	1236.8	8943.3	9627.9	115.8
ADRC2	0.5042	1222.0	9174.1	9646.4	177.6
MOADRC	0	1222.4	9164.5	9643.4	175.8

Table 6. Comparison of the rejection the coal quality change.

Load	100%		50%		0%	
Disturbance	Sine	Step	Sine	Step	Sine	Step
Simm	[−18, 6]	[−18, 11]	[0, 11]	[−18, 17]	[−2, 0]	[−18, 18]
MOPI2	[−17, 2]	[−18, 11]	[−4, 5]	[−18, 17]	[0, 14]	[−18, 17]
ADRC2	[−16, 5]	[−14, 11]	[−18, 7]	[0, 4]	[−17, 16]	[−18, 18]
MOADRC	[−17, 6]	[−14, 11]	[−18, 8]	[−17, 17]	[−1, 18]	[−18, 18]

Table 7. Comparison of coal quality flexibility J_{CQ}.

Scheme	Simm	ADRC2	MOADRC
J_{CQ}	137	144	163

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