Preprints of the 10th IFAC International Symposium on Dynamics and Control of Process Systems
The International Federation of Automatic Control
December 18-20, 2013. Mumbai, India

Selection of Control Structure of Elevated Pressure Air Separation Unit in an IGCC Power Plant for an Economical Operation

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Abstract: IGCC (Integrated Gasification Combined Cycle) is an alternative power generation system that can utilize fossil fuels in a more eco-friendly way than the conventional pulverized coal-fired plant. An IGCC plant requires an (Elevated Pressure) Air Separation Unit (EP ASU) that separates the air into pure oxygen and nitrogen, to be sent to the gasifier and the gas turbine, respectively. The ASU consumes about 10% of the gross power output generated in IGCC, so an economical operation of the ASU is important for lowering the overall power generation cost. In this research, controlled variable selection for an EP ASU is studied from the viewpoint of economics, i.e., with the objective of maintaining an economically (near-)optimal operation in the presence of load changes. Instead of the full-scale real-time optimization (RTO), we adopt a simpler approach known as self-optimizing control (SOC), which attempts to achieve the objective through a systematic selection of controlled variables. For the purpose of designing and testing a self-optimizing control structure, equation-based modeling of EP ASU is carried out using the software platform of gPROMS. Then, the SOC approach is applied based on the model to select the best set of controlled variables, which will lead to the most economical operation in the presence of load changes. Finally, PI control loops are designed and their dynamic control performances are tested. In addition, the economic loss in the presence of load changes is analyzed and compared with that achievable from the use of RTO.

Keywords: IGCC Power Plant; Elevated Pressure Air Separation Unit; Dynamic Simulation; Self-optimizing Control; Operating Cost

1. INTRODUCTION

Integrated Gasification Combined Cycle(IGCC) is one of the promising alternatives to utilize fossil fuel for electricity generation in a more eco-friendly way. IGCC plants are known to give higher energy efficiency than the conventional pulverized coal-fired (PC) power plants (estimated to be about 40% vs. 37%). An IGCC system is composed of a gasification unit, an air separation unit(ASU), a syngas purification unit, and a combined cycle involving a gas turbine and a steam turbine. Despite the promise, commercial adoption of IGCC has been limited and the keys to its more prevalent use are the cost reduction and stable operation. Currently, the cost of electricity made by IGCC is not low enough to compete with the conventional coal-fired power plant. More capital and operating costs are required for IGCC though the fuel cost is less than a PC power plant. NRTL reports that more than 80% of total electricity use within an IGCC plant is consumed by the ASU system. This amount represents more than 10% of the gross power output in a typically-sized IGCC plant.(NRTL, 2007) Naturally, ASU is the part that has received lots of attention for optimization and control studies.

The ASU produces highly pure oxygen, usually at 95% purity, to be fed to the gasification unit. In a cryogenic condition, an ambient air is separated into pure oxygen and nitrogen product through two-stage distillations. The ASU includes several gas compressors, which compress feed and products to high pressures of about 20$\sim$60 bar. This compressing energy is mainly responsible for the high operating cost of the ASU. Elevated pressure ASU (EP ASU) have proposed as an alternative to the conventional ASU system. The operating pressure of EP ASU (10$\sim$15 bar) is higher than that of the conventional system (5$\sim$6 bar). The raised pressure can save the compressing energy, especially when the ASU is integrated with the gas turbine to receive a high-pressure air feed. However, the EP ASU presents some additional control challenges due to a high degree of integration and consequently higher complexity.(Coca et al., 1998)

In this research, we study the problem of control structure selection for an IGCC's ASU system with a focus on the operating cost. For a unit of such high economic importance, it is sensible to consider the economics explicitly (in addition to the controllability) in selecting the control structure. Previous control studies on ASU have not considered the economics explicitly in selecting the control structure and designing the controllers. A standard way to integrate economics into control is to design a real-time steady-state optimizer (typically a linear program) and connect it with dynamic controllers. However, effective use of RTO (Real-Time Optimization) in an industrial setting is known to be difficult due to complications such

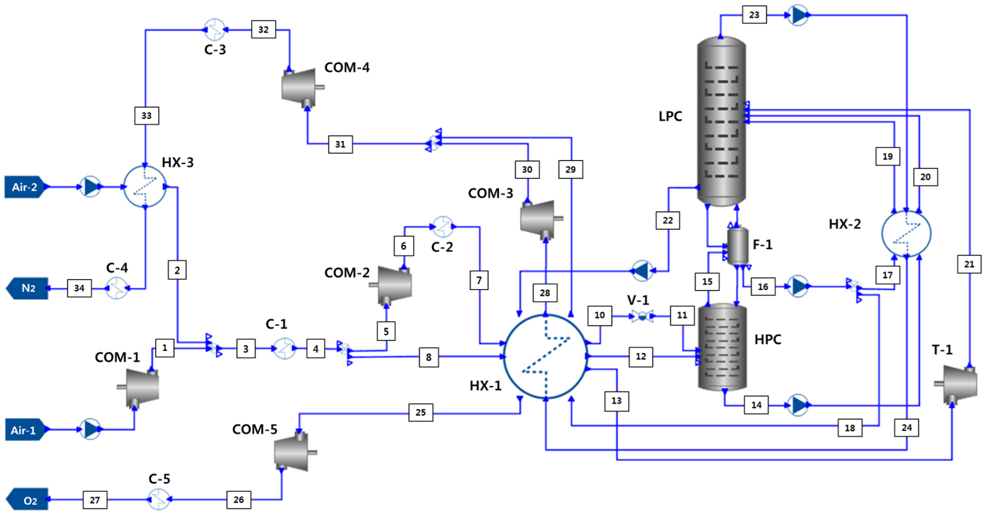

Fig. 1. Overall process flow sheet of EP ASU in an IGCC power plant

as potential inconsistencies between the optimizer layer and the regulatory layer and increased complexity for the operators. Here we opt for a simpler and more manageable option of self-optimizing control to select a set of controlled variables, which will ensure near-optimal operations, in spite of disturbances and load changes, when controlled to their set-points. In particular, an ASU system originally the number of controlled variable candidates are more than of available manipulated variables (Table. 1 and 2), so it may have a large potential to obtain economical benefits by applying Self-optimizing control.(Skogestad, 2000)

For the purpose of this study, we built an equation-based dynamic model of the EP ASU system on the commercial simulation platform of gPROMS. Self-optimizing control is applied to this model to screen through all the potential controlled variable sets and reduce to a small number of candidates, from the viewpoint of minimizing the operating cost (in the presence of oxygen load decrease scenarios) in addition to their controllability. The final selection is made by calculating the economic loss figures for all the candidates through rigorous simulations. Controllability of the selected control structure is verified by designing PI controllers and running closed-loop simulations under oxygen load decrease scenarios. We also examine the degree of potential economic loss by opting for the simpler control structure instead of the full-scale real-time economic optimization coupled with model-based controllers.

2. PROCESS AND PROBLEM DESCRIPTION

2.1 Process Description

The core part of the ASU system is a cryogenic rectification column. The cryogenic rectification column consists of two distillation columns and is operated at near 100 K. The flow sheet of the ASU system is given in Figure 1. The details of the overall process of EP-ASU are described in NRTL (2007), Rubin et al. (2007) and Mahapatra and Bequette (2013). Assumptions in this study are as below.

(1) The level of nitrogen integration between EP ASU and the gas turbine (GT) is 100%.
(2) Nitrogen product rate, not the nitrogen purity, should be controlled for the gas combustion unit operation.
(3) 1 kg/s of nitrogen product can be substituted by 1 kg/s of makeup steam at the gas combustor.

For modeling the cryogenic rectification column, modified equation-based model given by B. Roffel is applied to our study. It is an equilibrium based tray tower model.(Roffel et al., 2007) Peng-Robinson equation of state (EOS) is selected as the physical property model for the simulation of the EP ASU system because it is appropriate for a mixture in a cryogenic condition. The overall simulation is performed on the gPORMS simulator.

2.2 Problem Definition

The aim of this study is to obtain the control structure that enables to control the overall EP ASU system for a chosen set of operation scenarios so that an economically optimal operation of the unit can be achieved. In particular, the targeted control strategy is the classical PI controller, which is simple and well accepted in industries. Firstly, all the potential manipulated and controlled variables in the EP ASU process are listed. Next, the cost function, constraints, and operation scenarios are analyzed. Then, as reference values, the minimum achievable operating costs for various scenarios are obtained by solving the optimization problems.

Degree of freedom analysis Initially, there are 22 available manipulated variables for control in the EP ASU process.(Table 1) On the other hand, there are 42 candidate controlled variables in the EP ASU process as below. (Table 2) Among the 22 available manipulated variables, three manipulated variables (MV5, MV6, and MV7) are assumed to be already assigned to control the liquid level control in HPC (CV40), LPC (CV41), and condenser/reboiler (CV42), respectively.

Air feed rate from gas turbine (MV2) which is one of the external feed streams is considered as a fixed value because it is associated with the GT compressor part which may cause another complex issue. Another manipulated variable of the splitting ratio in PHX (MV4) which determines the flow rate of stream 12 and 13, is considered as a fixed variable as well. MV4 at its nominal state is determined as 0.95. When a disturbance occurs, the operating range of MV4 is too small (the upper range of change is just 0.05), so it is anticipated that MV4 cannot be effective in control. LPC bottom rate (MV9) should control the oxygen production rate for satisfying the oxygen load from the gasification unit, so it should be excluded from this analysis. The other remaining 16 (22-6=16) manipulated variables participate in the next analysis step along with the 39 (42-3=39) candidate controlled variables.

Definition of cost function and constraints For a meaningful problem definition of controlled variable selection for economic operations, cost function J to be minimized should be chosen. In this study, the cost function is the hourly operating cost spent by the whole EP ASU system. J is defined formally in Equation (1). The symbols are defined in the nomenclature table (Table 9).

$$J = \sum_i p_{elec} W_{load,i} + \sum_j p_{cw} Q_{duty,j} + p_{steam} \Delta F_{N_2} - p_{elec} W_{Turbine} \quad (1)$$

subject to the following constraints,

(1) Oxygen product specification
   (a) Purity : $z_{O_2} \geq 0.95kg/kg$
   (b) Temperature : $T_{O_2} \leq 390K$
   (c) Pressure : $P_{O_2} \geq 65bar$
(2) Nitrogen product specification
   (a) Temperature : $T_{N_2} \leq 450K$
   (b) Pressure : $P_{N_2} \geq 26bar$
(3) Flow direction
   $P_{T-1} \geq P_{LPC,20}$, $P_{H-1,Hot} \geq P_{HPC,20}$
(4) COM-1 outlet pressure, $P_{COM-1} \geq 16.2bar$
(5) C-1 outlet temperature, $T_{C-1} \leq 308K$
(6) COM-3 outlet pressure, $P_{COM-3} \geq P_{H-1,Cold}$
(7) C-3 outlet temperature, $T_{C-3} \geq 365.8K$
(8) V-1 outlet pressure, $P_{V-1} - P_{HPC,15} \geq 4bar$
(9) Non-negative constraints

The hourly operating cost is calculated as sum of the total compressing cost, total cooling cost, nitrogen makeup cost, and power generation cost. The electricity price p_{elec} is set as the generation cost for the IGCC power plant because the electricity used in the EP ASU is directly from the IGCC plant. (NRTL, 2007) The coolant used is assumed to be the water. Nitrogen makeup cost is calculated to take on both positive and negative values. When the nitrogen production rate becomes greater than the nominal level due to certain disturbances, less makeup steam can be used, and vice versa. The expander turbine generates a small amount of electricity during the depressurization of air stream split at the PHX, H-1. It has a negative effect on the operating cost.

Table 1. Available manipulated variable list in EP ASU process

Manipulated variable		Unit
MV1	Ambient air feed rate	Air-1
MV2	Air feed rate from gas turbine	Air-2
MV3	Split ratio in air splitter	S-1
MV4	Split ratio in PHX	HX-1
MV5	Split ratio in nitrogen splitter	S-2
MV6	HPC top rate	P-1
MV7	HPC bottom rate	P-2
MV8	LPC top rate	P-3
MV9	LPC bottom rate	P-4
MV10	Main air compressor load	COM-1
MV11	Boost air compressor load	COM-2
MV12	Low pressure nitrogen compressor load	COM-3
MV13	Nitrogen compressor load	COM-4
MV14	Oxygen compressor load	COM-5
MV15	Expander turbine load	T-1
MV16	Air cooler duty	C-1
MV17	BAC cooler duty	C-2
MV18	Primary nitrogen cooler duty	C-3
MV19	Secondary nitrogen cooler duty	C-4
MV20	Oxygen cooler duty	C-5
MV21	Reflux ratio in condenser/reboiler	F-1
MV22	Valve position	V-1

Table 2. Candidate controlled variable list in EP ASU process

Controlled variable		Stream, unit
CV1	Sub air feed rate to HPC	S5
CV2	Main air feed rate to HPC	S12
CV3	Expanded air feed rate to LPC	S13
CV4	MAC outlet temperature	S1
CV5	Mixed air stream temperature	S3
CV6	Air cooler outlet temperature	S4
CV7	BAC outlet temperature	S6
CV8	BAC cooler outlet temperature	S7
CV9	PHX hot outlet temperature	S10, S12, S13
CV10	PHX cold outlet temperature	S25,S28, S29
CV11	Valve outlet temperature	S11
CV12	HPC bottom temperature	S14
CV13	Condenser/reboiler inlet temperature	S15
CV14	HPC top temperature	S16
CV15	SHEX hot stream outlet temperature	S19, S20
CV16	SHEX cold stream outlet temperature	S24
CV17	Expander turbine outlet temperature	S21
CV18	LPC bottom temperature	S22
CV19	LPC top temperature	S23
CV20	O_2 cooler outlet temperature	S27
CV21	LP N_2 compressor outlet temperature	S30
CV22	N_2 mixer outlet temperature	S31
CV23	N_2 compressor outlet temperature	S32
CV24	Primary N_2 cooler outlet temperature	S33
CV25	Secondary N_2 cooler outlet temperature	S34
CV26	MAC outlet pressure	S1
CV27	BAC outlet pressure	S6
CV28	Adiabatic expansion valve outlet pressure	S11
CV29	HPC pressure	HPC
CV30	Expander turbine outlet pressure	S21
CV31	LPC pressure	LPC
CV32	O_2 compressor outlet pressure	S26
CV33	LP N_2 compressor outlet pressure	S30
CV34	N_2 compressor outlet pressure	S32
CV35	HPC top product purity	S16
CV36	HPC bottom product purity	S14
CV37	LPC top product purity)	S23
CV38	LPC bottom product purity	S22
CV39	N_2 product purity	S31
CV40	HPC liquid bottom holdup	HPC
CV41	LPC liquid bottom holdup	LPC
CV42	Condenser/reboiler liquid holdup	F-1

Identification of operational scenarios In the nominal condition, it is assumed that the EP ASU production of oxygen is run at its full capacity (968 tons/day). When the electricity demand for the IGCC plant decreases, less coal will be gasified into syngas. Hence, the oxygen production rate in the EP ASU should be reduced in a corresponding manner. In this study, 5%, 10% and 15% decreases in the oxygen production rate are considered in the operation scenarios.

Active constraint and the optimal operating conditions It can be argued that, in order to minimize the hourly operating cost J, several controlled variables should be controlled at their limits set by the constraints given in Equation (1) (so called "active constraints".) For example, T_{O_2} needs to be controlled at its upper bound (of the constraint 1-B) because the cooling duty of the oxygen cooler, C-5, should be minimized to minimize the operating cost. Another constraint, 1-A, is also assumed to be an active constraint under the optimal operation. To produce oxygen of higher purity in the LPC, lower pressure is favored. However, lower operating pressure of the LPC means increased power loads at the O_2 compressors (COM-5) and LP N_2 compressor (COM-3) due to the decreased the inlet pressures of the compressors. Therefore, oxygen purity which is same as the LPC's bottom product purity (CV38) should be controlled at its lower limit of 95%. All the assumed active constraints are listed in Table 3. At the same time, some of the other controlled variable candidates should be excluded from the consideration when these variables are chosen to be controlled at the limits of their constraints. For instance, if the LPC bottom purity (CV38) is controlled, then it is practically very hard to control the LPC top product purity at the same time because the top and bottom product purities strongly interact with each other. The controlled variable candidates excluded due to such considerations are listed in Table 3.

Table 3. The list of active constraints and related controlled and manipulated variables

Constraint	Bound	CV index	Excluded CV index	Pre-paired MV
1-A	Lower	38	37	8
1-B	Upper	20		20
1-C	Lower	32		14
2-A	Upper	25		19
2-B	Lower	34		13
4	Lower	26	4,5	10
5	Upper	6		16
6	Lower	33	21,23	12
7	Upper	24		18
8	Lower	28		22

Following the guidelines for input-output pairing suggested by de Araujo et al. (2007), the manipulated variable pairings for the 10 controlled variables can be chosen, as listed in Table 3. After such *a priori* assignment, the number of remaining controlled variable candidates is 24 (39-15=24). In addition, the degree of freedom also reduces to 6 (16-10=6), which are listed in Table 4. From the remaining 24 controlled variable candidates, six should be chosen and therefore 134,596 (24C6) possible candidate sets still exist. To get reference cost values, the optimal steady state values of these variables and corresponding cost value are found for each load change case by using the nonlinear optimization solver provided by gPROMS. The latter is can be found in Table 7.

Table 4. Remaining degree of freedom (manipulated variable) participating the optimization

	MV	Unit
MV1	Ambient air feed rate	Air-1
MV3	Split ratio in air splitter	S-1
MV11	Boost air compressor load	COM-2
MV15	Expander turbine load	T-1
MV17	BAC cooler duty	C-2
MV21	Reflux ratio in condenser/reboiler	F-1

3. METHODOLOGY DESCRIPTION

Self-optimizing control (SOC) is a methodology to select controlled variables, which are to be kept at constant set-points during the operation, so that near-optimal operation with an acceptable loss (with respect to some well-defined cost function) can be maintained in the presence of several selected disturbances and set-point changes.(Skogestad, 2000) As a first step, the optimization problem needs to be defined, as the cost function $\min_u J(u, d)$ subject to the constraints $g(u, d) \leq 0$. u contains the available manipulated variables (degrees of freedom for the optimization) and d the disturbance variables. SOC searches for the control structure (choice of controlled and manipulated variables) giving the minimum loss L, which is defined as the cost with the selected controlled variables minus the optimal cost as shown in Equation (2).(Halvorsen et al., 2003)

$$L(u, d) = J(u, d) - J_{opt}(u_{opt}, d) \approx \frac{1}{2} e_c^T J_{cc} e_c = \frac{1}{2} \|z\|_2^2 \quad (2)$$

where

$$J_{cc} = (G^{-1})^T J_{uu} G^{-1}$$

$$z = J_{uu}^{1/2}(u - u_{opt}) = J_{uu}^{1/2} G^{-1}(c - c_{opt}) = J_{uu}^{1/2} G^{-1} e_c$$

G is the steady-state gain matrix and J_{uu} is the hessian matrix of the cost function J with respect to u.

There are two methods to distinguish the loss. One is a simple method and the other is an exact local method. In this study, the simple method is used to select the controlled variables. In the simple method, it is assumed that every manipulated variable in u has a same effect on the cost function, such that J_{uu} a scalar times the identity, as a result of proper scaling of the manipulated variables u and the controlled variables c. Under this assumption, the worst-case loss is

$$\max_{\|e_c'\|_2 \leq 1} L = \max_{\|e_c'\|_2 \leq 1} \frac{1}{2} \|z\|_2^2 = \frac{1}{2} \left[\sigma_1 (J_{uu}^{1/2} G'^{-1})\right]^2$$
$$= \frac{1}{2} \left[\sigma_1 (\alpha^{1/2} G'^{-1})\right] = \frac{1}{2} \frac{1}{\sigma_n G'^2} \quad (3)$$

where σ_1 is the largest singular value and σ_n is the smallest singular value of a $n \times n$ matrix. G' is a scaled static gain matrix calculated with a diagonal scaling matrix D_c for the controlled variable and D_u for manipulated variable, as

$$G' = D_c^{-1} G D_c \quad (4)$$

The way to calculate the two diagonal scaling matrices is mentioned in Appendix of Halvorsen et al. (2003). To find the minimum loss case, we should maximize $\sigma_n(G')$. Generally, one has a large number of possible controlled variable sets to choose from. The static gain matrix G' was obtained through the simulation on gPROMS, and the singular values were calculated by the *SVD* function in MathWork's MATLAB software.

4. RESULT

4.1 Identification of candidate controlled variables

Screening of controlled variable sets There are 134,596 possible controlled variable sets left. Before calculating the smallest singular value of the static gain matrix of each possible set, the number of candidates is further reduced by eliminating a large number of sets that are physically and practically impossible due to certain operational characteristics. Table 5 shows groups of the controlled variables that fall under such considerations. The category

Table 5. List of controlled variable group for filtering impractical sets

Group	CV index	Choice	Limitation
1	1, 2, 3	Compulsory	Lack of MV
2	29, 31	Compulsory	Thermal interaction
3	12, 13	Optional	Temperature profile
4	35, 36	Optional	Purity profile
5	35, 39	Optional	Lack of MV
6	14, 15	Optional	Lack of MV
7	18, 19	Optional	Temperature profile
8	16, 19	Optional	Lack of MV
9	17, 30, 31	Optional	Lack of MV
10	7, 27	Optional	Lack of MV
11	10, 22	Optional	Lack of MV

'compulsory' means that at least one controlled variable should be chosen out of the group. On the other hand, the 'optional' category gives the option of not selecting any of the controlled variables in the group. For group 1, only one controlled variable can be selected because there is only one available manipulated variable able to control the feed rate to the HPC. Groups 5, 6, 8, 9, 10, and 11 are similar cases. For group 2, it is difficult to control the pressures of both columns simultaneously. The two columns are thermally integrated at the condenser/reboiler and their interaction is too strong for them to be controlled simultaneously. Hence, only one of the pressures should be chosen as the controlled variable. For groups 3, 4, and 7, it is not necessary to select both variables in the group. For example, in group 3, if temperature of the HPC bottom product is controlled, condenser/reboiler inlet temperature is determined automatically. This means that it is redundant to control both of them. The above exercise reduces the number of viable sets from 134,596 to 2,205 to which the SOC calculation is actually applied. The smallest singular value of the scaled static gain matrix G' of these cases are calculated to identify a few top candidates, for which rigorous simulation based analysis can be performed.

Rank of the smallest singular values The smallest singular value of the scaled static gain G' for each controlled variable set was calculated by the *svd* function in MATLAB. The size of scaled gain matrix G' is 6×6. The best 10 controlled variable sets in terms of the minimum singular value criterion are listed in Table 6. The two controlled

Table 6. List of the best 10 CV sets

Rank	1st	2nd	3rd	4th	5th	6th	$\sigma_6 \times 100$
1	**CV1**	CV8	CV11	CV15	CV19	**CV29**	10.627
2	**CV1**	CV8	CV11	CV15	**CV29**	CV30	10.446
3	**CV1**	CV8	CV15	CV27	**CV29**	CV30	10.300
4	**CV1**	CV8	CV15	CV19	CV27	**CV29**	10.289
5	**CV1**	CV10	CV11	CV15	CV19	**CV29**	10.200
6	**CV1**	CV10	CV11	CV15	**CV29**	CV30	10.070
7	**CV1**	CV8	CV19	CV27	**CV29**	CV30	9.750
8	**CV1**	CV10	CV15	CV27	**CV29**	CV30	9.389
9	**CV1**	CV8	CV14	CV27	**CV29**	CV30	9.351
10	**CV1**	CV10	CV15	CV19	CV27	**CV29**	9.350

* σ_6 is the 6th singular values which is the smallest singular value and obtained by SVD using MATLAB.

variables common in the 10 best sets are sub air feed rate to the HPC (CV1) and HPC pressure (CV29). The choice of the other four controlled variables vary among the sets. The 10 best sets are considered as the final candidates in the next step.

4.2 Loss evaluation

For the 10 selected controlled variable sets, the loss values (as defined in Equation 2) can be calculated with respect to each of the three oxygen load changes by running the steady-state simulations in a corresponding manner (*i.e.*, by fixing the chosen CVs at their setpoint values). The evaluated hourly operating costs for the three oxygen load changes for each set are shown in Table 7. In the

Table 7. Evaluation of the hourly operating cost for the best CV sets

Hourly operating cost ($/hr)	**Load change level**		
CV set list	5%	10%	15%
1		Infeasible	
2	3859.15	3723.89	3590.90
3∼5		Infeasible	
6	3860.23	3725.41	3592.44
7		Infeasible	
8	3970.16	3946.29	3923.81
9	3972.56	3950.51	3929.17
10		Infeasible	
Optimal case	3699.93	3572.71	3451.80

simulation, some of the CV sets gave infeasible results. Infeasible here means that there is no solution satisfying the given constraints. For example, the control structure with the best predicted loss value does not give a feasible solution. The split ratio of the N_2 splitter is being bounded to 1. With such a control structure, however, the bottom liquid holdup level of LPC can no longer be controlled. The reason why these infeasible sets were chosen is that the SOC method does not consider the operational constraints in the formulation. It simply estimates the expected loss with respect to the optimal case, assuming that the chosen CVs can be controlled to their respective setpoints. The more complex the studied process, the more infeasible sets may pass through. If much of the screening performed in our analysis had been skipped, more infeasible cases would have shown up in the final selections.

After excluding the six infeasible sets (1, 3, 4, 5, 7 and 10), the four remaining sets are 2, 6, 8 and 9. It is verified that, for these CV choices, it is possible to satisfy all the constraints in the presence of the oxygen load change scenarios. From Table 7, the 2nd best set shows the smallest loss with respect to the load changes, and this is in agreement with the ranking by the self-optimizing control analysis. However, the loss difference between the 2nd and the 6th best sets (referred to hereafter as the 1st CV candidate group) are small and it would be a matter of control ease. In addition, the 8th best set and 9th best set (referred to as the 2nd CV candidate group) do similarly. Though the 1st CV group and the 2nd CV group are all ranked within the top 10 CV sets given by the self-optimizing control analysis, the annual loss differences are not negligible. (Around \$900,000∼\$2,900,000)

4.3 Controlled variable selection including controllability analysis

For the oxygen load change, the controllability of the selected controlled variable set is validated by the dynamic simulation using gPROMS. In the previous section, three liquid holdup levels and ten controlled variables that are associated with the active constraints are already paired with certain manipulated variables. The input-output pairings for the selected controlled variables (given by CV set 2 in the previous section) are listed in Table 8. The pairing was done through RGA analysis. To keep all the 19 controlled variables at their setpoints, 19 PI controllers were designed and implemented in the gPROMS simulator. The closed-loop dynamics were simulated by introducing the the oxygen production rate changes as ramp signals. The simulations showed that all the controlled variables could be controlled to their setpoints with time-lags of about 9,000∼20,000 seconds (2.5∼5.5 hours before the CVs converged to their set-points). This control solution should work well assuming the time scale of load changes at the IGCC power plant is such that the above settling time is acceptable.

Table 8. MV-CV pair of the final selection

Pair index	CV index	MV index
1	1	3
2	8	17
3	11	11
4	15	21
5	29	1
6	30	15

Table 9. Nomenclature

Symbol	Definition	Unit & Value
J	Hourly operating cost	\$/kg
p_{elec}	Electricity price	\$0.0779/kWh
p_{CW}	Cooling duty cost	$\$1.15 \times 10^{-6}$/kWh
p_{steam}	Steam production cost for N_2 makeup	\$100/((kg/s)hr)
$W_{load,i}$	Power load of compressor i	kW
$Q_{duty,j}$	Cooling duty of cooler j	kW
$W_{turbine}$	Power load of turbine	kW
ΔF_{N_2}	Actual N_2 product rate − Nominal N_2 product rate	kg/s

5. CONCLUSION

In this paper, a control study for the economical operation of the elevated pressure air separation unit (EP ASU) in an IGCC power plant was presented. To obtain a manageable control structure in an efficient manner, the method of self-optimizing control was applied. The method was effective in reducing the number of controlled variable sets from a very large number (more than in thousands) down to just a few, to which rigorous nonlinear simulation / optimization based analysis could be applied. Through the loss evaluation and controllability considerations, the best controlled variable set among the surviving candidates was chosen. It was verified that self-optimizing control indeed pointed to appropriate choices of CV sets for which economic losses were small (for the chosen load changes). To verify the feasibility of the chosen control structure, 19 PI controllers were designed and installed on the simulator and the closed-loop performance was checked. This analysis will be extended to the entire IGCC plant model in the future.

ACKNOWLEDGEMENTS

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0006839).

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