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Agile control of CO_2 capture technology for maximum net operating revenue

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Abstract: This paper uses a multi-layered control scheme consisting of model predictive control (MPC) and mixed integer non-linear programming (MINLP) for the analysis of power plant net operating revenue when retrofitted with a post-combustion carbon capture (PCC) plant. The capability of the proposed control scheme is examined for 24-hour operations of an integrated plant (power plant with PCC) in the years 2011 and 2020. The control scheme is tested in response to variability in upstream power plant dynamic loads. The agility of the control scheme subject to forecast 2020 electricity and carbon prices is shown to result in yearly net operating revenue of approximately 12% of the gross revenue. Whereas, the same integrated plant generates a net operating revenue loss of roughly 13% of the gross revenue under 2011 electricity and carbon prices.

Keywords: Algorithm, Automatic control (close-loop engineering), Optimization devices, Plant wide, Multi-input multi-output system, Nonlinear system.

1. INTRODUCTION

Low emissions fossil fuel technologies such as post combustion CO_2 capture (PCC) are expected to play a significant role in combating climate change. Recently, a 'carbon capture ready' power plant emerged as a noteworthy solution towards curbing global warming (Markusson and Haszeldine 2010). However, profitability of operation needs to be understood and costs reduced for this type of plant to come to commercially feasible scale and operation.

This study uses a multi-layered control scheme consisting of model predictive control (MPC) and mixed integer non-linear programming (MINLP) for the analysis of 660 MW coal-fired power plant net operating revenue when retrofitted with amine-based PCC plant. Where, the power plant provides part of its power to PCC plant operation via steam turbine bleed. The higher layer (MINLP) computes optimal CO_2 capture rate, *CC* and power plant net load at given electricity and carbon prices with the ultimate objective to obtain maximum net operating revenue (ideal revenue). While, the bottom layer (MPC embedded with PCC plant) regulates lean solvent flowrate and reboiler heat duty to ensure the PCC plant operates in a way to achieve identical net operating revenue as the ideal net operating revenue. This paper demonstrates the agility and robustness of the control scheme in maximising revenue of operation while matching the load and considering carbon price input.

2. DEVELOPMENT OF A MULTI-LAYERED CONTROL SCHEME

The objective function at the high layer that maximizes net operating revenue is described in (1).

$$Max\ (Revenue) = \int P_e * (Power\ plant\ net\ load - PCC\ penalty) * dt - \int C_t * CO_2\ emitted * dt - P_{PP} - P_{PCC} \quad (1)$$

Where P_e is the price of electricity and C_t is the carbon price (CO_2 allowance). The net operating revenue composite consists of three individual costs which include P_{PP} as the power plant operational cost,, P_{PCC} as the PCC operational cost and finally, the cost of CO_2 emission (indicated in the second integration term). The first integration term in the above equation represents the revenue generated through selling of electricity. Here, we optimize the operational cost of integrated plant where it is then used to determine the net operating revenue of the system. Fig. 1 illustrates the operation of MPC scheme (bottom layer).

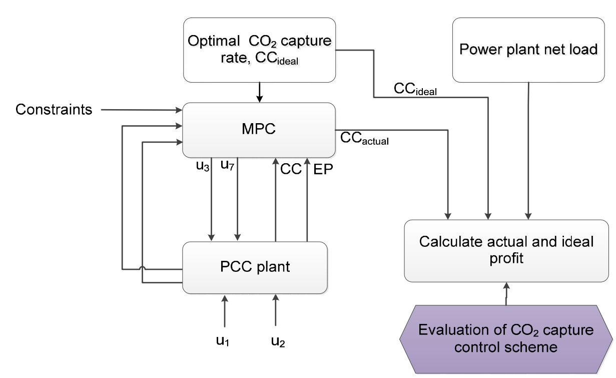

Fig. 1. MPC architecture (u_1: flue gas flow rate, u_2: CO_2 concentration in flue gas, u_3: lean solvent flow rate, u_7: reboiler heat duty, *CC*: CO_2 capture rate, *EP*: energy performance).

The innovative features of this work are that it offers a temporal multiscalar multi-layered control scheme critical for top-down management decision making and operation of coal-fired power plant integrated with PCC. Where, the top and bottom layers consider different interval times; 30 minutes and 10 seconds respectively. This big transmission of interval time imposes a challenge to MPC scheme to respond proactively to internal and external upsets stemming from the integrated plant. A comprehensive explanation

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pertaining to this multi-layered control scheme can be found in (Abdul Manaf, Qadir et al. 2016).

3. CASE STUDY

3.1 Annual flexible operation mode

The agility of the proposed control scheme is tested in response to variability in upstream power plant dynamic loads based on annual flexible operation mode of the integrated plant. The case study was demonstrated based on 2011(-\$147/ MWh - \$ 12,136/MWh) and 2020 (\$3/MWh - \$17,959/MWh) electricity prices. For the year 2020, the projected electricity prices were estimated by assuming a 5% yearly increment from the base year 2008 (Australian Energy Market Operator (AEMO)). Carbon price for year 2011 was adapted and extracted based on European Union Allowance (EUA) historical data available in Intercontinental Exchange Futures Data. For the year 2020, a hypothetical carbon price trend was estimated by assuming a 5% yearly increment and 3% inflation rate induced yearly from the base year 2008. This estimation is based on the core policy scenario proposed by the Treasury Department, Australia (The Treasury).

4. RESULT AND DISCUSSION

4.1 Annual flexible operation mode

Figs. 2-3 show the outputs from the multi-layered control scheme for year 2011 and 2020 respectively. For year 2011, it can be observed that the power plant operated in load following mode for a high proportion throughout the year. This reflects that during load following operation, power plant combined with PCC generated low cost corresponding to its prevailing electricity and carbon prices. Short-term maintenance (shutdown) plans were observed during month of May, June, July and December. For year 2020, the power plant is operated in recurrent maximum load with intermittent narrow unit turndown and load following. This result is particularly relevant to power plant operation since energy systems do not all operate in the same way (Mac Dowell and Shah 2015). Moreover, these mixed operation modes of power plant in line with scheduled shutdowns are actually assisting to reduce the running cost of both power plant and PCC. Both these dataset (power plant load profile and CO_2 capture rate) obtained in this study are beneficial for future insight if 'carbon capture ready' power plants are to become a reality. Where, these analyses/data may serve as a baseline or reference information to the contractor, engineer and plant operator during design, commissioning and troubleshooting stages.

At the bottom layer, for both years, the MPC scheme has shown satisfactory control performance in tracking the ideal CO_2 capture rate (CC_{ideal}). It can be observed that the lean solvent flow rate, u_3 and reboiler heat duty, u_7 were compensating each other in responses to set point changes of CO_2 capture rate. The responses showed that the lean solvent flow rate is relatively more sensitive compared to the reboiler heat duty in its reaction to the fluctuation of CO_2 capture set point (CC_{ideal}). In other words, lean solvent flow rate gives a faster/ahead response than the reboiler heat duty. The benefit of employing MPC scheme and the agility performance in terms of plant net operating revenue is explained in the next sub-section.

4.2 Net operating revenue – MPC performance

Agility performance of the MPC scheme was evaluated based on the deviation in ideal and actual net operating revenue (controller error). From (1), the total plant net operating revenue was segregated into four individual terms as given in (2).

$$(PP + PCC)Rev = A - B - C - D \tag{2}$$

Where A represents the plant revenue generated through selling of electricity, B is cost of CO_2 emission (carbon price paid), C and D are the power plant and PCC operational costs respectively.

Fixed, ideal and actual gross revenue of operation and the resultant net operating revenue of the system for year 2011 and 2020 are presented in Table 1. Fixed operation mode (base condition) was performed by implementing 90% capture rate throughout one-year operation. This was implemented by constraining the lower and upper bounds of CO_2 capture rate at 90% while maintaining the objective function (maximize net operating revenue) at corresponding power plant loads. It can be observed, for flexible mode, the system subject to 2020 electricity and carbon prices generated annual net operating revenue of approximately 12% of the gross revenue. While for 2011, the system incurred a net operating revenue loss roughly 13% of the gross revenue. This negative net operating revenue occurred possibly because of the lower bounds set for the power plant output (0 MW) and CO_2 capture rate (25 %). For instance, during times of very low electricity prices (possibly even negative), the cost of operation of the power plant and PCC plant would exceed the revenue generated from selling the electricity. As expected, net operating revenue forecasted from fixed operation mode (year 2011 and 2020) is much lower compared to that in flexible operation mode. This outcome illustrates that the application of flexible operation mode enhances plant net operating revenue and provides significant cost saving.

Capture energy penalty and other main performance parameters for the power plant associated with PCC are listed in Table 1. The fixed operation mode has a capture penalty of 9%, being 0.1% higher than the flexible operation mode (actual) for year 2011 and 2020 respectively. Where, those energy penalties fell within the range of the state of the art amine-based technology (3.0 - 4.5 MJ/kg CO_2). Besides that, via MPC scheme, PCC plant (in flexible operation mode) was capable of attaining average of 84% from the ideal cumulative CO_2 capture in both years, concurrently obtaining high net operating revenue compared to the fixed operation mode. MPC scheme exhibited superior control performance by minimizing the controller error to an average of 4% for both years. This is illustrated based on the deviation between ideal and actual net operating revenue from which the agility