Steady-State Analysis of Industrial MPC Controllers

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Abstract

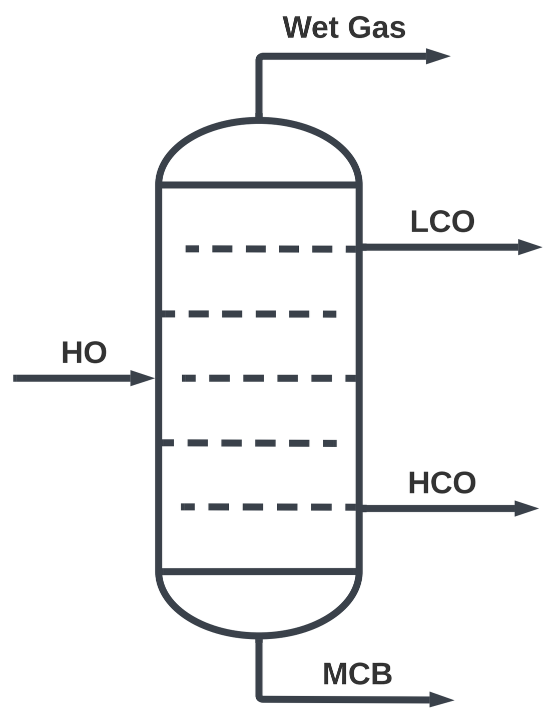
This work focuses on the definition and solution of the optimization problem that calculates the optimal steady-state values of controlled (CV) and manipulated (MV) variables for industrial process unit at Slovnaft refinery. An analysis of constraints is performed on the optimal values of CVs and MVs, considering ideal constraints (based on technical documentation), while by manipulating them (because, for example, a disturbance occurre), the operator creates real constraints (currently used constraints in control). The aim of this analysis is to find out which real constraints are not optimally set (compare to ideal constraints) and how they affect the decrease in profit generated during operation.

Thesis link

Distillation Column

- integral part of the Fluid Catalytic Cracking unit,
- processes heavy oil (HO) feed into wet gas, light (LCO) and heavy (HCO) circulation oil, main column bottom (MCB) products.

Variables	No.
Controlled (CV)	23
Manipulated (MV)	11
Disturbance (DV)	13



Distillation Column.

Steady-State Calculation

The calculation of the optimal steady-state values of CVs and MVs is modeled using quadratic programming with safety regions and soft constraints. The optimization problem mimics steady-state operation of Honeywell's Profit Controller.

$$\begin{aligned}
\min_{CV,MV,\epsilon,E} \quad & \sum_{i=1}^{s} b_{CV,i} CV_i + \sum_{i=1}^{s} a_{CV,i}^2 (CV_i - CV_{0,i})^2 \\
& + \sum_{j=1}^{t} b_{MV,j} MV_j + \sum_{j=1}^{t} a_{MV,j}^2 (MV_j - MV_{0,j})^2 \\
& + \sum_{i=1}^{s} Q_{CV,H,i}\, E_{CV,H,i} + \sum_{i=1}^{s} Q_{CV,L,i}\, E_{CV,L,i} \\
& + \sum_{j=1}^{t} Q_{MV,H,j}\, E_{MV,H,j} + \sum_{j=1}^{t} Q_{MV,L,j}\, E_{MV,L,j} \\
\text{s.t.} \quad & CV_i - CV_i^{SS} = \sum_{j=1}^{t} K_{i,j} \cdot \left(MV_j - MV_j^{SS}\right), \\
& CV_{L,i} + \Delta CV_{L,i} - \epsilon_{CV,L,i} \leq CV_i \leq CV_{H,i} - \Delta CV_{H,i} + \epsilon_{CV,H,i}, \\
& MV_{L,j} + \Delta MV_{L,j} - \epsilon_{MV,L,j} \leq MV_j \leq MV_{H,j} - \Delta MV_{H,j} + \epsilon_{MV,H,j}, \\
& 0 \leq \epsilon_{CV,H,i}, \quad 0 \leq \epsilon_{CV,L,i}, \\
& 0 \leq \epsilon_{MV,H,j} \leq \Delta MV_{H,j}, \quad 0 \leq \epsilon_{MV,L,j} \leq \Delta MV_{L,j}, \\
& -E_{CV,H,i} \leq \epsilon_{CV,H,i} \leq E_{CV,H,i}, \quad -E_{CV,L,i} \leq \epsilon_{CV,L,i} \leq E_{CV,L,i}, \\
& -E_{MV,H,j} \leq \epsilon_{MV,H,j} \leq E_{MV,H,j}, \quad -E_{MV,L,j} \leq \epsilon_{MV,L,j} \leq E_{MV,L,j}.
\end{aligned}$$

Any constraint (MV_L, MV_H, CV_L, CV_H) can be specified by its ideal (IDHL, IDLL) value from technological specifications or by actual (HL, LL) value set temporarily by operators.

Constraints Analysis

When constraints are intentionally shifted (e.g. IDHL → HL), real constraints can create a profit loss. Therefore, it is necessary to analyze the effectiveness of their setting in the following steps:

- substitute each real constraint for an ideal one and calculate the value of the objective function,
- detect a change in the value of the objective function before and after the change (and calculate its value),
- provide a recommendation to the supervisor to restore the constraint based on the change in the value of the objective function.

Results

The detected losses in each time sample are prioritized according to their influence on the change in the value of the objective function. The supervisor is provided with textual information to correct the constraints.

List of profit losses in operation sorted in descending order by the loss size.

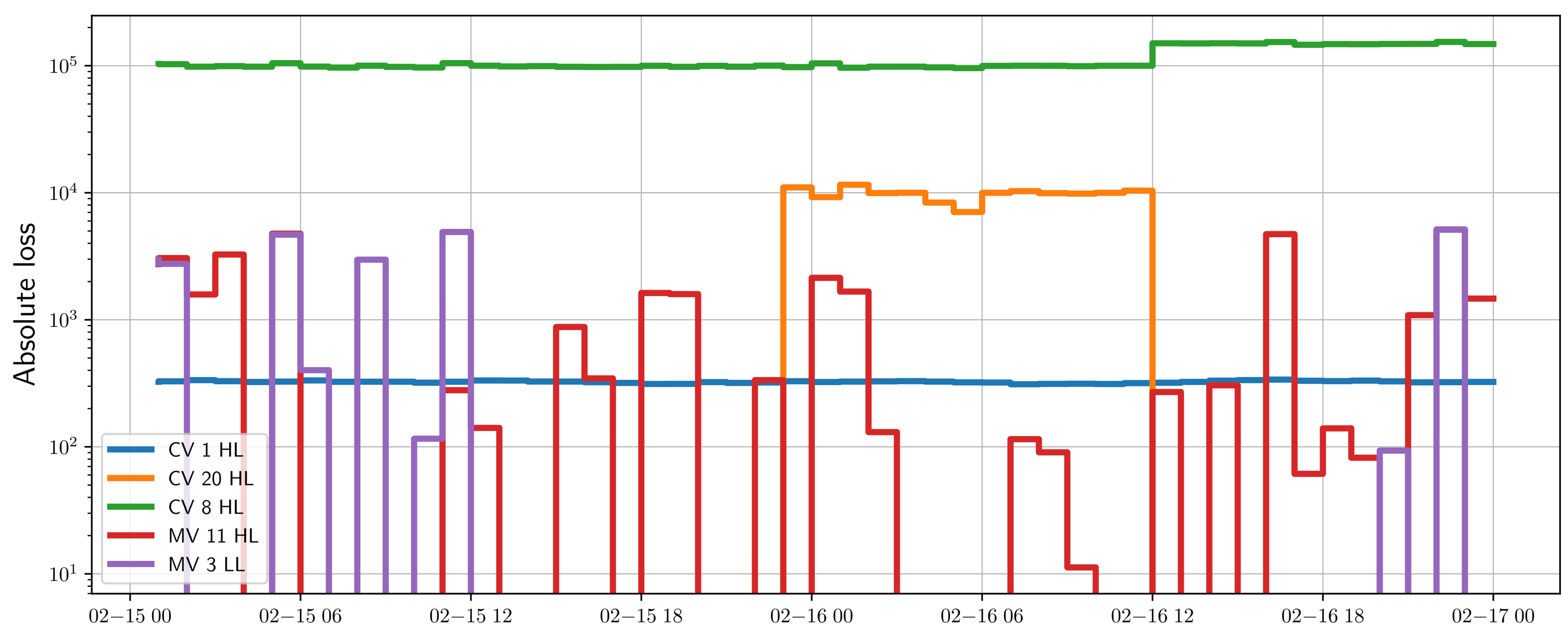
Priority	Var.	Limit	Abs. Loss	Rel. Loss	Recommendation*
1	CV 8	HL	90206.8	$9.02 \cdot 10^{-6}$	**Move HL to IDHL.**
2	MV 3	LL	18693.8	$1.87 \cdot 10^{-6}$	**Move LL to IDLL.**
			...		
6	CV 1	HL	325.1	$3.25 \cdot 10^{-8}$	**Move HL to IDHL.**

Note*: Recommendation refers to the shift of the constraint (e.g. Move HL to IDHL. means that by moving the real high constraint to the ideal high constraint, the loss is reduced.)

For a time series of data, the supervisor has at his disposal a list of long-term losses (a continuous loss that appears during a specific time interval), including information about the number of intervals, how many times the long-term loss appeares for each constraint across all time data (text, graphs):

List of time intervals of long-term profit losses.

Var.	Limit	Int.	Initial Time	Final Time
MV 11	HL	1	2022-02-15 11:59:59	2022-02-16 00:59:59
MV 11	HL	2	2022-02-16 12:59:59	2022-02-16 23:59:59
		...		
CV 1	HL	1	2022-02-15 01:00:00	2022-02-16 23:59:59



Development of the absolute value of the loss of profit control for each constraints.

Conclusions

This paper deals with the calculation of optimal steady-states of CVs and MVs, including the analysis of the constraints of such an optimization problem. When implementing soft constraints, ϵ deviation was penalized absolutely. The analysis of the effectiveness of setting constraints has shown that shifting ideal constraints to real ones can in specific cases lead to a loss of profit during control. Information about inappropriately set constraints is provided to the supervisor in tabular and graphical form, for analysis in each time sample of data and during the time series of data.

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