OPTIMAL AVERAGING LEVEL CONTROL OF CHLORINE DIOXIDE STORAGE TANKS

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ABSTRACT

Chlorine dioxide (ClO₂) storage tanks provide a buffer between the supply, namely the chlorine dioxide generator, and the demand, namely the bleach plant. Optimal averaging level control can ensure that fluctuations in the demand of the bleach plant are effectively absorbed by the available ClO₂ storage capacity. That is, the ClO₂ production target is manipulated by increments that are never larger than the required value to keep the storage level within assigned limits. Consequently, the smooth manipulation of the production target improves the efficiency and stability of the ClO₂ generator. Mill-based case studies exemplify the controller tuning, and illustrate the behaviour of the selected averaging level control strategy.

Keywords:

Storage tanks, Chlorine Dioxide Generators, Process Control, Bleach Plants, Level Indicators, Efficiency, Controllers.

INTRODUCTION

Chlorine dioxide (ClO₂) is used in the pulp and paper industry as a bleaching agent. It is an unstable compound which, for practical reasons, must be manufactured at the mill site [1]. Due to the relatively high costs of the raw chemicals used in ClO₂ manufacture, it is important to have the generator operating at high efficiency. Under normal operation (decompositions excluded), generator efficiency is believed to be determined by two main factors: the operating point for chemical concentrations in the reactor, and the variability in these concentrations [2]. Optimal targets for chemical concentrations are either given by the manufacturer of the generator or obtained through practical experimentation. Once the concentration targets are set, variability reduction becomes paramount in maintaining high generation efficiency.

Some advances in the control of ClO₂ generators have recently been reported, which address the control of chemical concentrations [3,4], and liquor level inside the generator [5,4]. The current report addresses the variations in ClO₂ production rate, which is determined by the level of ClO₂ solution in the storage tanks. Large storage tanks provide buffering between fluctuations in ClO₂ demand and its generation. A significant change in the production rate tends to upset the normal operation of the generator, at least until all low-level control loops reach a new steady-state operation. The generator efficiency decreases during these upsets, which is mainly due to fluctuations in the concentration of chemicals in the reactor. Therefore, it is important to avoid significant changes in the production rate through efficient use of the available ClO₂ storage capacity.

The vast majority of control strategies address the problem of driving one or more process outputs toward desired setpoints, through the manipulation of one or more process inputs. A notable exception occurs in averaging level control of storage tanks. In this control strategy, the main goal is to reduce, as much as possible, variations in the manipulated flow, by efficiently using the available storage capacity. Therefore, optimal averaging level control is an appropriate solution for controlling the level in the ClO₂ storage tanks. This document provides a brief introduction to single-vessel chlorine dioxide generators, followed by a description of the control strategy and mill-based case studies that exemplify the success of the application.

THE CHLORINE DIOXIDE GENERATOR

Figure 1 shows a simplified schematic diagram of a chlorine dioxide generator, where methanol (CH₃OH) is used to reduce sodium chlorate (NaClO₃) in an acidic solution (H₂SO₄). The heart of the process is a titanium reactor, which combines ClO₂ generation, sodium sesquisulfate crystallization, and evaporation in a single vessel.

The main body of the generator is essentially a forced-circulation evaporator. A solution of sodium chlorate and methanol is fed into the recirculation loop, as well as sulphuric acid. Immediately upon acid addition, chlorine dioxide is formed so that the mixture returning to the generator body contains a significant volume of ClO₂ gas and
water vapour. This gas mixture enters a vapour space above the liquor and is separated from unreacted material that falls back into the liquor reservoir. Gases from the top of the generator pass into an indirect contact cooler where the water vapour is condensed. The ClO₂ gas then passes into an absorption tower, where it is dissolved in chilled water forming a solution that is sent to storage.

**CLO₂ STORAGE TANK LEVEL CONTROL**

The control algorithm selected for this application is Paprican’s optimal averaging level control (ALeC), which is a model-based algorithm that provides optimal flow filtering based on the minimization of the maximum rate of change of the manipulated flow (see the appendix for more information on ALeC). The primary goal of ALeC is to use the storage capacity in order to absorb disturbances in the flows, whereas to drive the level towards setpoint is only a secondary goal. Figure 2 shows a typical block diagram of the ClO₂ storage tank averaging level control. Notice that the flow of methanol is the main variable determining the ClO₂ production rate, provided the concentration of chlorate and acid in the generator liquor are within specified ranges. ALeC manipulates the inlet flow of the storage tanks by adjusting the ClO₂ production target, which, in turn, sets the methanol feed rate. The dynamics of the generating process are completely neglected, as the settling time of the ClO₂ generator for a change in methanol flow was identified to be less than 5 minutes, whereas the settling time of the level control is in the order of several hours.

![Figure 2. Block diagram of the ClO₂ storage tank averaging level control.](image)

ALeC’s internal algorithm must operate with a consistent set of units for level and volumetric flow, which are usually metres (m) and cubic metres per minute (m³/min), respectively. Therefore conversion factors must be used in order to transform the usual operational units of the ClO₂ storage tank application, into a consistent set of units.

The first conversion factor relates percent of storage to the lower limit for ClO₂ generation. Bottom: the green line is the flow of chlorate, the production target, the green line is the measured production, and the red dotted line is the lower limit for ClO₂ generation. Besides the conversion factors, the design of the averaging level controller requires knowledge of the tank dimensions, selection of the level and flow constraints, and selection of the following tuning parameters: sampling time (T_s), controller settling time (T_c), and estimator settling time (T_e). Guidelines for the selection of these parameters are provided in the appendix.

**INDUSTRIAL EXAMPLE**

The first application of ALeC on ClO₂ storage tanks was on an industrial generator designed to produce 45 metric tonnes of ClO₂ per day. Prior to the implementation of averaging level control in the ClO₂ storage tanks, a PID controller was being used to drive the storage level towards setpoint. Figure 3 shows that the controller was doing a good job of keeping the storage level near its setpoint, at the cost of aggressively manipulating the ClO₂ production target. This effect is most evident around Day 2, when the storage level is very close to its setpoint and the production target is constantly being modified to keep the level tightly controlled.

![Figure 3. PID control of the ClO₂ storage tanks.](image)
Besides tight level control, there are two other factors influencing the process behaviour shown in Figure 3: a) the eight-hour-period oscillations in the process variables were mostly being originated by the generator liquor level control [5], and b) the actual ClO₂ production was lagging its production target because the chlorate flow, instead of the methanol flow, was being used as the master variable to control ClO₂ production. These two issues were addressed in parallel to the implementation of the averaging level control strategy.

The ClO₂ storage is comprised of three identical storage tanks that are linked at their base. Each tank has a diameter of 6.1 m (20 feet), which implies that the cross-sectional area of the three-tank combination is 87.6 m². The height of each tank is 15.5 m (51 feet), but the height from the base of the tank to the bottom of the overflow pipe is 14.8 m (48 feet and 8 inches). This latter quantity perfectly matches the base of the tank to the bottom of the overflow pipe is 14.8 m (48 feet and 8 inches). This latter quantity perfectly matches the height from the base of the tank to the bottom of the overflow pipe is 14.8 m (48 feet and 8 inches). This latter quantity perfectly matches the height from the base of the tank to the bottom of the overflow pipe is 14.8 m (48 feet and 8 inches).

The maximum step-disturbance expected to happen at the ClO₂ storage tanks is the start-up or shut-down of the bleaching process: \( \Delta Q = 2.19 \text{ m}^3/\text{min} (30 \text{ t/d}) \). Given that the nominal buffering capacity is 130 m³ (based on a level setpoint of 80%, and level constraints at 70% and 90%), this particular application has a hold-up time of 59.4 minutes. As seen in the appendix, the hold-up time sets reference values for the design of the ALeC tuning parameters. Table I summarizes the values chosen for these tuning parameters.

### Table I.

<table>
<thead>
<tr>
<th>ALeC tuning parameters</th>
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<tbody>
<tr>
<td>( T = 10/60 \text{ min} )</td>
</tr>
<tr>
<td>( T_e = 2 \text{ min} )</td>
</tr>
<tr>
<td>( T_c = 900 \text{ min} )</td>
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</table>

A hold-up time of 59.4 minutes implies a recommended sampling time of less than 3.0 minutes, which is well above the implemented value of 10 seconds. If the level estimator is well designed, there is almost no penalty on having a small sampling time apart from an increase in usage of the controller processing unit.

The critical value for the controller settling time, in this application, is 594 minutes, and the actual value for the settling time was chosen to be 900 minutes. This choice implies that whenever the storage level is at setpoint, a step-disturbance of at least 1.44 m³/min (19.7 t/d) will cause ALeC to use the whole nominal buffering capacity. A second controller settling time was added to ALeC, during this application, due to an operational request from the mill. This new controller settling time, called \( T_c^* \), is only in effect when ALeC is activated (switched from manual to auto) and the measured level is outside the allocated boundaries. Under this circumstance, \( T_c^* \) determines how fast the level will be brought to setpoint, instead of \( T_c \). As soon as the measured level is within the allocated boundaries, ALeC switches into normal operation and \( T_c^* \) becomes ineffective, even if the level goes temporarily outside the limits. The value of \( T_c^* \) should obviously be less than or equal to \( T_c \), and in our application it was chosen to be 300 minutes.

Given that the noise component in the level measurement is quite low, the estimator settling time \( (T_e) \) was chosen to be 2 minutes. The software “ALeC Design Tool” (Figure 4) was used throughout the design of the controller for its capability of simulating the control response. Another useful feature of the software is the computation of the estimator gains (right-hand side of the screen) based on the selected estimator settling time.

![Figure 4. Screen shot of ALeC Design Tool.](image)

The control algorithm was implemented on the distributed control system available at the mill. Figure 5 shows a week of operation of the storage tanks under optimal averaging level control. In contrast to Figure 3 (same scales are used in both figures), it is evident that the production target is now being manipulated in a much smoother way. This has immediate consequences in the way the chemical flows are manipulated as well. At the end of the sixth day there is a sequence of disturbances that force ALeC into taking somewhat aggressive action in order to keep the storage levels within the allotted boundaries. The performance of the controller can be regarded as highly satisfactory.

Given that the actual production of ClO₂, in t/d, is not being directly controlled, the measured production might deviate from its target. An instance of this behaviour is evident in Figure 5. From the level-control perspective, this deviation does not pose an actual problem because ALeC will
simply bias the production target, so that the actual production meets the demand of the level controller.

EFFECTS OF CHANGES IN THE CONCENTRATION OF THE ClO$_2$ SOLUTION

The concentration of the ClO$_2$ solution directly affects the conversion factor from the production rate, a mass flow, to the volumetric flow of solution feeding the storage tank. The relationship between the setpoint for the ClO$_2$ concentration, in g/L, and the conversion factor is:

$$\text{FlowConv}(t) = \frac{1}{1.44} \frac{\text{ClO}_2}{\text{SPT}}$$  \hspace{1cm} (4)

If $[\text{ClO}_2]_{\text{SPT}}$ varies during normal operation, then an immediate transfer of those changes into the conversion factor causes sudden moves in the output of the averaging level controller. This happens because ALeC unintentionally makes immediate corrections to the manipulated production target in order to keep a constant flow of ClO$_2$ solution. This behaviour is shown in Figure 6, where the concentration of the ClO$_2$ solution is changed, stepwise, from 9.5 g/L to 7 g/L.

An unsophisticated solution to this problem would be to ignore the changes in the ClO$_2$ concentration, and use a constant conversion factor. In such a case, the performance of the averaging level controller becomes sub-optimal. The effect of mismatches in the conversion factor must be analyzed case-by-case, but as a general rule, observed from simulations, it is better to overestimate the value of the concentration, than to underestimate it.

The most appropriate solution to the problem is actually to modify the control algorithm (see the appendix) such that the available storage capacity is used for absorbing changes in that concentration. This modification is quite simple to implement, and involves the following steps:

Step 1: At the beginning of each iteration, calculate the current flow conversion:

$$\text{FlowConv}(t) = \frac{1}{1.44} \frac{[\text{ClO}_2]}{\text{SPT}}$$  \hspace{1cm} (5)

Step 2: At the end of each iteration, convert the manipulated flow from m$^3$/min into t/d:

$$U(t) = \frac{Q_m(t)}{\text{FlowConv}(t)}$$  \hspace{1cm} (6)

Step 3: Just before the calculation of the flow imbalance, (A.8), adapt the previous manipulated flow according to the current flow conversion:

$$Q_m(t-T) = U(t-T) \cdot \text{FlowConv}(t)$$  \hspace{1cm} (7)
Figure 7 shows a simulation of this proposed solution, which can be contrasted with the simulation in Figure 6. This solution has been implemented on an industrial generator that does not contain a water chiller. Figure 8 shows smooth manipulation of the methanol flow despite several large changes in the ClO₂ solution strength.

Figure 8. Industrial data confirms that ALeC is able to use the storage capacity in order to absorb fluctuations in the concentration of the ClO₂ solution.

CONCLUSIONS

Optimal averaging level controllers, like ALeC, can effectively coordinate the usage of the available ClO₂ storage capacity, and therefore provide an optimized buffer between the demands of the bleach plant, and the generation of chlorine dioxide. Mill-based case studies show the potential of the proposed control strategy, in comparison to tight level control. An economic analysis of the improved controls for these ClO₂ generators is provided in a separate report [2].

ACKNOWLEDGEMENTS

The authors wish to thank John Ball for his help in collecting some of the data presented in this report. They also acknowledge Moncef Chioua for his careful technical review of the manuscript.

REFERENCES

APPENDIX: OPTIMAL AVERAGING LEVEL CONTROL

The details of Paprican’s optimal averaging level control (ALeC) are documented references [6] and [7]. ALeC combines a model-predictive averaging level control algorithm [8] with a standard estimator. This appendix presents the controller’s tuning parameters, provides guidelines on the design of those parameters, and then summarizes the steps performed by the control algorithm.

ALeC is a model-based controller that provides optimal flow filtering based on the minimization of the maximum rate of change of the manipulated flow. Depending on the application, the manipulated variable can be either the inlet or the outlet flow of the storage tank (see Figure A.1). Given that ALeC is a model-based controller, it requires knowledge of the tank dimensions: height and cross-sectional area. In addition to the tank dimensions, ALeC requires information on the level and flow constraints, as well as the following tuning parameters: sampling time \( T \), controller settling time \( T_c \), and estimator settling time \( T_e \). Guidelines are available for the selection of these parameters, based on the maximum expected disturbance \( \Delta Q \), and the nominal buffering capacity \( V_c \). The maximum expected disturbance corresponds to the maximum step-disturbance expected in the uncontrolled flow to/from the storage tank. The nominal buffering capacity is the volume available in the storage tank between the nominal level setpoint and the level constraint that will become active during the occurrence of \( \Delta Q \).

![Diagram of ALeC](image)

Figure A.1. ALeC can manipulate either the inlet flow (left) or the outlet flow (right) of the storage tank. Even if measured, the uncontrolled flow is not used in the control algorithm.

The ratio between the nominal buffering capacity and the maximum expected disturbance is the main parameter characterizing the tuning of ALeC. This ratio is called the hold-up time, \( T_h \), which is the time it takes for the maximum expected disturbance, at the uncontrolled flow, to use the nominal buffering capacity under no control action:

\[
T_h = \frac{V_c}{\Delta Q}. \tag{A.1}
\]

From practical experience, the controller sampling time, \( T \), is recommended to be less than or equal to one twentieth of the hold-up time:

\[
T \leq \frac{T_h}{20}. \tag{A.2}
\]

The controller settling time, \( T_c \), determines the amount of time available for the controller to bring the level back to setpoint, therefore getting the storage tanks ready for the next incoming disturbance. The larger the value of the settling time, the smaller the flow manipulations will be. For a given \( \Delta Q \), there is a critical value for the settling time, \( T_c^* \), above which ALeC will use the whole nominal buffering capacity \( V_c \), assuming that the tank level is at setpoint when \( \Delta Q \) occurs. It is recommended that:

\[
T_c > T_c^*, \tag{A.3}
\]

so as to effectively use the available storage capacity. The exact expression for \( T_c^* \) is somewhat complex, but the following expression is an excellent approximation to the critical value:

\[
T_c^* \approx 5(2T_h - T). \tag{A.4}
\]

Conversely, for a given \( T_c \) it is possible to calculate the smallest step-disturbance that uses the whole nominal buffering capacity:

\[
\Delta Q \approx \frac{10V_c}{T_c + 5T}. \tag{A.5}
\]

ALeC contains an internal estimator that filters noisy measurements of the storage level and obtains estimates of the current level and uncontrolled flow. The estimator can be designed by any one of the methods described in [7], but the easiest method is the so called hybrid estimator, which requires a single tuning parameter, the estimator settling time, \( T_e \). This parameter determines the time it takes for the estimator to track a step disturbance in the uncontrolled flow of the storage tank. The estimator settling time reflects a compromise between filtering of the level measurement and the speed of detecting new disturbances. That is, low noise levels require little filtering (small \( T_e \)), which implies a fast detection of disturbances. As a rule of thumb,

\[
T_e \leq \frac{T_h}{2}. \tag{A.6}
\]

The best way to assess the effect of \( T_e \) is via simulations, and the use of the dedicated program “ALeC Design Tool” is highly recommended for this purpose. That software also contains several alternative methods for the design of the estimator.

The following table summarizes the main variables related to ALeC. The distinction between off-line and on-line parameters refers to the current status of the controller implementation, and is subject to change in the future.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Off-line</th>
<th>On-line</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_h )</td>
<td>Time available for the controller to bring the level back to setpoint</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_c )</td>
<td>Controller settling time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_e )</td>
<td>Estimator settling time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta Q )</td>
<td>Maximum expected disturbance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( V_c )</td>
<td>Nominal buffering capacity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The steps performed by the control algorithm, at each sampling time, are the following:

1. Estimate the current level and unmeasured flow. The level estimate, \( \hat{x}_1 \), and the unmeasured-flow estimate, \( \hat{x}_2 \), are obtained by filtering a noisy measurement of the storage level, \( h \):

\[
\hat{x}_1(t) = \hat{x}_1(t-T) + \frac{T_e}{S} [\hat{x}_2(t-T) - Q_m(t-T)]
\]

\[
e(t) = h(t) - \hat{x}_1(t-T)
\]

\[
\hat{x}_2(t) = \hat{x}_2(t-T) \pm k_2 e(t)
\]

(A.7)

where the estimator gains, \( k_1 \) and \( k_2 \), can be obtained by any one of the methods described in [7]. For the hybrid estimator, it is possible to obtain approximate values for these gains:

\[
k_1 \approx 1 - e^{-a}, \quad a = \frac{3\sqrt{2} T}{T_e}
\]

\[
k_2 \approx \frac{3}{S} \left[ 1 + e^{-a} - 2e^{-a/2} \cos \left( \frac{a}{2} \right) \right]
\]

2. Calculate the estimated flow imbalance, \( \hat{Q}_e \):

\[
\hat{Q}_e(t) = \pm \left[ \hat{x}_2(t) \pm Q_m(t-T) \right].
\]

(A.8)

3. Compute the nonlinear control action.

3.1. Determine which is the active level constraint, \( h_{lim} \):

\[
h_{lim} = \begin{cases} h_{max} & \text{if } \hat{Q}_e(t) > 0, \\ h_{min} & \text{otherwise.} \end{cases}
\]

(A.9)

3.2. Calculate the number of samples to reach the active level constraint:

\[
k^* (t) = \left[ \frac{2S[h_{lim} - \hat{x}_1(t)|t]}{T \hat{Q}_e(t)} \right].
\]

(A.10)

where \( \lceil y \rceil \) indicates the smallest integer greater than or equal to \( y \).

3.3. Calculate the minimum control action needed to stop the level from exceeding the active level constraint:

\[
\Delta Q^*(t) = \frac{2\hat{Q}_e(t)}{k^*(t)} - \frac{2S[h_{lim} - \hat{x}_1(t)|t]}{Tk^*(t)[k^*(t) + 1]}.
\]

(A.11)

4. Compute the linear control action.

4.1. Calculate the prediction horizon:

\[
P = \frac{T_e}{2.5T_e}.
\]

(A.12)

4.2. Calculate the control action that forces the level to setpoint within the controller settling time:

\[
\Delta Q(t) = \frac{2\hat{Q}_e(t)}{P + 1} - \frac{2S[h_s - \hat{x}_1(t)|t]}{TP( P + 1)}.
\]

(A.13)

5. Choose the largest of the control actions:

\[
\Delta Q(t) = \begin{cases} \Delta Q^*(t) & \text{if } \left| \Delta Q^*(t) \right| > \left| \Delta Q(t) \right|, \\ \Delta Q(t) & \text{otherwise} \end{cases}
\]

(A.14)

\[
\hat{Q}_m(t) = Q_m(t-T) \pm \Delta Q(t).
\]

6. Clamp the manipulated flow:

\[
Q_m(t) = \begin{cases} Q_{max} & \text{if } \hat{Q}_m(t) > Q_{max}, \\ Q_{min} & \text{if } \hat{Q}_m(t) < Q_{min}, \\ \hat{Q}_m(t) & \text{otherwise.} \end{cases}
\]

(A.15)

\[\]