PREDICTIVE ON-OFF COST MINIMIZING CONTROL OF A MUNICIPAL WASTE WATER TREATMENT PLANT

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Abstract: With intermittently operated municipal waste water plants the aeration switching sequence should be optimized under the constraints that the solved nitrogen concentration in effluent has to be kept within its environmental limits. This is a highly nonlinear control problem because of the nonlinear biological process model ASM1 (Activated Sludge Model 1), the on-off state of the manipulated sequence and the concentration constraints. The constrained optimization was transformed to the unconstrained optimization of the predictive on-off control, as the violations of the constraints were converted to their economical costs. Furthermore, the cost of the aeration was considered in the cost function. Copyright © 2005 IFAC

Keywords: predictive control, municipal waste water treatment, nonlinear models.

1. INTRODUCTION

A municipal sewage plant is usually a WWTP (Waste Water Treatment Process) with an intermittently operated nitrification/denitrification process. For this class of processes an on-off controller is used to switch the aeration on or off or to set the reference value for a conventional PI-controller which controls the concentration of the solved oxygen in the biological reactor.

In most cases the on-off controller works between two limit values, an upper and a lower boundary or switching point. These boundary values are generally set empirically in such a way that the values of the effluent of the plant are kept within their legal limit values.

One possible way for the optimization based on the whole ASM1 model (Henze et. al. 1987) is shown by Fikar, Chachuat and Latifi (2002) and Latifi (2003). They show in an example of a small-sized alternating treatment plant the possibility to save costs by reducing the on-time of an on-off-controller, which controls the aeration. Therefore, they fixed the number of cycles and limited the minimum of the on- and off-time to 15 min and the maximum to 120 min. Another method for optimization is exemplified on a simplified model, which is based also on the
ASM1 is shown in Lukasse, Keesman and Straten (1999). With this model the number of the parameters has been reduced and the unknown parameters were estimated recursively. Besides a cost function based on the one-step-ahead predicted concentrations was optimized. In Kim et al. (2000) also a reduced model was used. In this case the fraction of the aeration time and the total cycle time has been optimized. Admittedly they also have demonstrated their optimization on a small-sized alternating sludge process in bench-scale unit.

In this paper a new optimizing algorithm is presented in order to find the best switching sequence using predictive model based simulations, and in order to directly search for the control which causes the least cost for the operator of the plant. This means that the cost factor of the cost function really has the unit of a currency, e.g. Euro (€).

2. THE INTERMITTENTLY OPERATED WASTE WATER TREATMENT PLANT

During the nitrification phase of the process a waste water basin is filled with oxygen, thus the basin is operated aerobic and ammonium is converted to nitrate. The denitrification phase is operated anaerobic. During the denitrification the NO₃ which is built during the nitrification, is converted to N₂.

In smaller waste water treatment plants the nitrification and denitrification phases are operated alternatively, thus the two stages of the nitrogen elimination process are separated chronologically and not spacially. This is realised by operating the activated sludge basin once aerobe and then anaerobe in turn. The switching between the aerobe and the anaerobe operation can be realised by a time schedule or by on-off control of the NO₃ concentration in the basin. Fig. 2 shows the scheme of such a nitrification/denitrification process operated intermittently.

![Fig. 2. Nitrification/denitrification part of the waste water treatment process controlled by a cascade structure of an on-off and a PI controller](image)

For the control of this process first a conventional on-off controller was used. The switching points for the controller were set to 1mg/l NO₃ for the lower switching point and 4mg/l NO₃ for the upper point. The interesting point of view is that legal limits exist for the total nitrogen concentration and for the solved NH₄ but not for NO₃ which is used for the on-off controller in this case.

For the simulation of the waste water treatment process the program package SIMBA of the Institute for Automation and Communication (IFAK) in Magdeburg, Germany, was used (Alex, To and Hartwig, 2002; Jumar and Alex, 2002). This program package is an add-on library for MATLAB/SIMULINK for a waste water treatment process.

3. THE COST-OPTIMIZATION OF THE WASTE WATER TREATMENT PLANT

The traditional idea of controlling an intermittently operated WWTP is to control the concentration of the NO₃ by using an on-off controller which is set to empirically discovered switching points, in order to keep the effluent concentrations in the legal limits. In this work the approach is not to achieve a better control of the NO₃-concentration but to achieve a more cost efficient control of the plant.

First we have to take a look at the actions which can produce costs and which really produce costs while the plant operates. The actions which can produce costs should be prevented completely and the actions which really produce costs should be minimized as well as possible.

The actions which can produce costs are:
- any violation of the legal limits of the total nitrogen concentration.
- any violation of the legal limits of the NH₄.

The actions which always produce costs are:
- the duration of aeration, because of the energy-consumption of the fan
- the number of switching on and switching off the aeration because each alternation of load rises the abrasion of the fan and therefore increases the costs.

With this background the cost function to be optimized is as follows:

\[
J = J_{\Sigma N} + J_{\Sigma NH_4} + J_{On-Off} + J_{On}
\]

with

\[
J_{\Sigma N} = \lambda_{\Sigma N} \sum_{i=1}^{l_{\text{end}}} \begin{cases} 
0 & \text{for } (c_{NO_3,i} + c_{NH_4,i}) \leq L_{\Sigma N} \\
1 & \text{for } (c_{NO_3,i} + c_{NH_4,i}) > L_{\Sigma N}
\end{cases}
\]
The weighting factors were used to calculate the real costs of the cost function (in this case in the currency “€”). In the explicit case the weighting factors were chosen to:

- \( \lambda_{\text{On-Off}} = 0.25€ \) costs for the higher abrasion of the fan,
- \( \lambda_{\text{On}} = 0.03€/\text{min} \) costs for the operation of the aeration.

Figures 3 to 6 demonstrate the mode of functioning of the cost function. The first two terms of the cost function rise only if the given limit is violated. In Fig. 3 (and zoomed in Fig. 4) it can be seen that the cost factor rises only in those sampling steps where the legal limit was violated.
time). It can be seen that the factor $J_{On}$ rises only in the points where the aeration is operating and that the factor $J_{On-Off}$ rises stepwise in the points where the aeration is switched on or off.

Fig. 6. Progression of the cost factors $J_{On}$ and $J_{On-Off}$ for lower relative switching on percent (about 25%)

The optimization of the cost function was performed online and predictive for the next 24 hours. That means the prediction and optimizing horizon were 24 hours while the sampling time was 5 min. However, the plant was simulated by the toolbox SIMULINK/SIMBA continuously and sampled afterwards. Fig. 8 shows the minimization of the cost function by using the genetic algorithm of Sekaj (2002). The optimization was started from the conventional on-off-control as shown in Fig. 8. The corresponding cost function was the initial value in Fig. 7.

Fig. 7. Reduction of the cost function during the genetic optimization process

4. SIMULATION AND OPTIMIZATION RESULTS

Figures 8 and 9 show the effluent concentrations NO₃, NH₄ and the total nitrogen concentration with a conventional on-off controller for 1 and 0.2 days, respectively. Figures 10 and 11 show the same effluent concentrations with the optimized manipulated variable for 1 and 0.2 days, respectively.

Fig. 8. Effluent concentrations with a conventional on-off controller for 1 day

Fig. 9. Effluent concentrations with a conventional on-off controller zoomed for 0.2 day’s

Fig. 10. Effluent concentrations with the optimized manipulated variable sequence for 1 day
It can be seen that the effluent concentrations are below the given legal limits with both the conventional and with the predictive on-off controller. Correspondingly the costs which can occur were prevented in both cases. But it can also be seen that the optimized manipulated variable sequence produces effluent concentrations which are significantly higher than the concentrations with the traditional on-off controller.

Figs. 14 and 15 show the reference and controlled signals of the oxygen concentration and the aeration rate for the conventional on-off controller for 1 and 0.2 day’s, respectively.
As it is seen in Figures 14 and 16 the mean value of the oxygen concentration reference signal in the biological reactor was reduced from 0.667 mg/l to 0.5 mg/l due to the predictive control.

The absolute number of switches did not decrease and was 16 in both cases but the duration of the aeration was significantly reduced from 425 min to 315 min, thus about by 35%. The aeration duration is proportional to the costs that really occur because of the aeration. As mentioned earlier, the task was to minimize these costs, as well.

5. CONCLUSION

It was shown, that a predictive on-off cost minimizing control is able to minimize the necessary costs of the aeration without violating the effluent concentration limit values given by the laws of the Ministry for Environment. Instead of a quadratic function the real costs of the operation were minimized. As a consequence the minimization could not be solved analytically and the optimal manipulated sequence (the duration of the aeration) was calculated iteratively by using a genetic algorithm.

In the case investigated the optimization resulted in slightly worse effluent concentrations than with conventional on-off control, but anyhow all concentrations were kept in their limits. On the other hand the optimization resulted in a significantly lower air inflow, which means that the costs of the aeration were relevantly reduced.

The evaluated cost function defines a summarization of the significant costs of an intermittently operated waste water treatment plant and is therefore a good basis for optimizations of municipal plants (of course there might be an adaptation necessary for the explicit cases).

6. ACKNOWLEDGMENTS

This project was supported by the Federal Ministry for Education and Research (BMBF) as promotion of Applied Research and Development, recommended by the German Federation of Industrial Cooperative Research Associations "Otto von Guericke". The authors thank also Dr. J. Alex from IFAK (Magdeburg, FRG) for his consultation on the modelling of the waste water treatment technology. The authors are thankful to Dr. I. Sekaj (Department of Automatic Control Systems, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology, Slovak Republic) for his help in applying the genetic algorithm for the case presented. The cooperation in the subject of predictive control with the Budapest University of Technology and Economics is supported by the University of Applied Science Cologne and by the program of EU-Socrates.

7. REFERENCES


