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Experiences of Self-tuning Control of an Activated Sludge Process

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Abstract. This paper discusses experiences in implementing self-tuning dissolved oxygen concentration control in a full scale wastewater treatment plant. After presentation of the control structure, the performance is discussed. Then a number of special problems are considered. The most serious one is a severe limitation in the air supply to the aerators. Other problems are mode transitions from manual to automatic mode and handling of large changes in the process output.

Keywords: Adaptive control, implementation, cascade control, PID control, pressure control, process control, saturation, chemical variables control, activated sludge, dissolved oxygen.

Introduction

Self-tuning dissolved oxygen (DO) control has been implemented on the activated sludge process at the Käppala Sewage Works, Lidingö, Sweden, which serves the northern parts of metropolitan Stockholm. This plant has six parallel activated sludge systems and five compressors in the air production system. The dynamics of the process is affected by several variables, i.e. influent flow rate, influent substrate concentrations, temperature, pH level, salinity etc. The major restrictions in plant operation are due to saturations in control signals and security measures to avoid surge in compressors.

A limited implementation of the control system was tested during 1983–84 and is reported in Olsson et al (1985) and Rundqwist (1985). This paper covers the full implementation which was finished in december 1986, see Rundqwist (1986). With minor exceptions it has been in operation since then.

The control system has improved plant performance and capacity. Excess aeration (waste of energy) and long periods of too low DO concentration (performance degradation) are avoided. Compressors are switched on and off automatically. Without the control system the plant now would have needed continuous three shift operation. This is due to a double plant load compared with 1984.

The paper is organized as follows. First the linear part of the control strategy is summarized and then DO control and air production control is discussed. Next a number of special problems are considered such as saturations in cascaded control loops, mode transitions, etc. Finally limitations in the air production are discussed. A number of solutions such as "windup on purpose", are used to overcome the problems.

Summary of the control strategy

The overall structure of the plant is shown in Figure 1. Compressors supply air for the aeration of the liquid in the tanks. The actuators are throttle valves and compressor guide vanes (or diffusors). Measured variables are DO concentrations, air flow rates, manifolder pressure and actuator positions.

The following control loops are used. Self-tuning DO control (6 loops) measures DO concentration and delivers

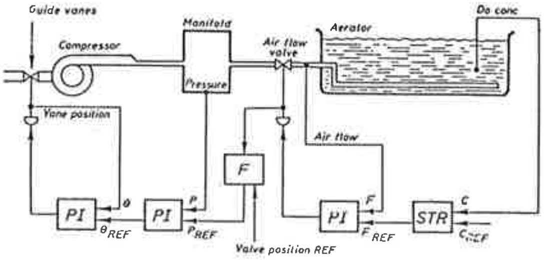

Figure 1. Block diagram of the Käppala plant.

an air flow rate set point. Air flow rate control (6 loops) adjust throttle valves to compensate for varying manifold pressure. Pressure control (1 loop) measures manifold pressure and delivers guide vane (and diffusor) position set points. Guide vane (and diffusor) controllers (4 loops) adjust their positions. The pressure minimization (1 loop) measures throttle valve positions and adjusts a pressure set point in order to keep the most-opened throttle valve almost wide open.

Both DO control and pressure minimization require operational air flow rate control. The DO controllers and the pressure minimization use constant set points, while all other controllers have cascaded set points. The air flow rate, guide vane and diffusor controllers are standard PID controllers. The other control loops are implemented in an Asea Novatune control computer. Both pressure control and pressure minimization use PID algorithms. The DO controllers are direct self-tuning algorithms with least squares identification, see Åström(1987). A synchronous sequence network switches compressors on and off. Full details of the control program is given in Rundqwist (1988).

Self-tuning DO concentration control

The DO dynamics is approximately described by the bilinear differential equation

$$\frac{dc}{dt} = -a_0 c + (a_1 F + a_2)(c_s - c) - R \qquad (1)$$

see Olsson (1984), where c is the DO concentration, c_s the DO saturation concentration, F the air flow rate and R the time-varying organism oxygen uptake rate . Parameters $a_0 \ldots a_2$ are time-varying.

Several phenomena like the air flow dynamics, the local stirring due to the air bubbles and the transportation delay of the liquid from the diffusor to the DO probe are neglected in the model. These phenomena are approximated by a time delay of a few minutes.

At the Käppala plant air flow changes typically settle in 10 s. The DO concentration approaches steady state in the range of 30–50 minutes. During the first 5 minutes a DO concentration step response does not look like first order. For larger time horizons a first order model with a time constant of about 15 minutes is an adequate description of the DO dynamics.

Implementation

Since the time scale for the air flow rate loop is much shorter than for the DO dynamics, air flow dynamics can be neglected when implementing DO control. The closed loop transfer function can be approximated by

$$H_m(q^{-1}) = \frac{(1-p)q^{-1}}{1-pq^{-1}} \qquad (2)$$

where p is the closed loop pole, and H_m has unit stationary gain. Since the respiration is a load disturbance, an integrating controller is required, e.g.

$$\hat{r}_0 \Delta u(t) = -\hat{s}_0 \Delta y(t) + (1-p)\left(u_c(t) - y(t)\right) \qquad (3)$$

where $\Delta = (1 - q^{-1})$, u is the control signal (air flow rate set point), y the process output (DO concentration) and u_c the (DO) set point, which is set by the operating personnel. Self-tuning controllers with integral action is discussed in e.g. Tuffs and Clarke (1985) and Rundqwist (1985). Parameters $\hat{r}_0$ and $\hat{s}_0$ are estimated by a LS algorithm from the prediction model

$$\Delta y(t+1) = \hat{r}_0 \Delta u(t) + \hat{s}_0 \Delta y(t) \qquad (4)$$

where the prediction horizon is 1 step ahead and the forgetting factor is 0.98.

The sampling interval must be fairly large. In the first control experiment at Käppala, the sampling interval was 10 minutes and the closed loop pole $p = 0$, which resulted in an oscillating control signal and process output. The sampling interval was subsequently changed to 12 minutes, and later to 15 minutes. Finally the pole p in 3 was chosen as 0.4. The oscillations then dissappeared. This sampling interval and closed loop pole location correspond to a solution time of 50 minutes, compared to 10 minutes in the first attempt. The solution time is the same magnitude as the open loop response time.

Evaluation

In earlier experiments it has been verified that automatic DO control reduces the average air flow demand and energy consumption compared with manual control. During unconstrained periods of self-tuning DO control the standard deviation was 0.02 mg/ℓ, which is roughly a factor 10 less than what has been reported using PID control, see Olsson et al (1985), Rundqwist (1985) and Rundqwist (1986).

When all six aerators are controlled they behave similarly, see Figure 2. The DO standard deviations are slightly higher than 0.02 mg/ℓ. Normally control is satisfactory, but deviations may occur during constrained periods, see Section about the compressors.

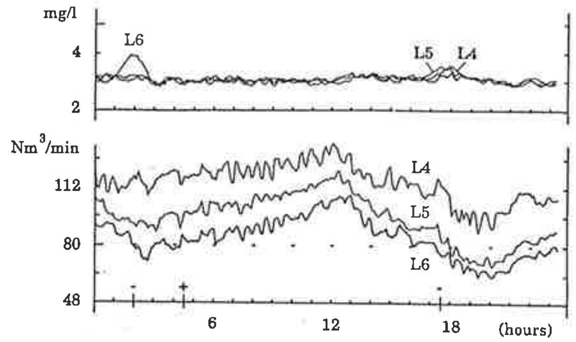

Figure 2. DO concentrations (upper curves) and air flow rates (lower curves) during self-tuning DO control of aerators L4–L6 at Käppala with sampling interval 15 minutes and pole location 0.4. The load variations are similar but not identical. Compressor starts (+) and stops (−) are indicated.

Different operating conditions

During standard operation controller parameters are approximately as follows; $\hat{r}_0 \in [2.5, 6.0]$ and $\hat{s}_0 \in [0.2, 0.5]$ and they usually vary similarly. During the fall of 1987, however, both nitrification and denitrification was utilized in aerator L6. This means a higher air flow rate than usual and a different air distribution in the aerator. Then parameter $\hat{s}_0$ was negative in the interval $[-0.35, -0.05]$ and parameter $\hat{r}_0$ in the interval $[5.0, 9.5]$, i.e. slightly higher than normal. One interpretation is that noise characteristics is different in these operating conditions.

Air production control loops

Pressure control is basically PID with a manifolder pressure measurement. The actuators are guide vanes and diffusors in two different types of compressors. The details of the implementation are described below. Normal operating pressures are 0.157 – 0.165 MPa, i.e. approximately 0.06 MPa overpressure. Occasionally slightly higher pressures are used. The sampling interval of the pressure controller is 1 second. The pressure set point is supplied by the pressure minimization. Under certain conditions the set point is constant.

Pressure minimization is a control loop which tries to keep the most opened throttle valve as open as possible. The pressure reference value is computed by a PI control law where the control error $e(t)$ is

$$e(t) = \varphi_{ref} - \max_i(\varphi_i(t)) = \varphi_{ref} - \varphi_{max} \qquad (5)$$

φ_i is the i:th throttle valve position and φ_{ref} is the desired position, see Figure 3. The controller gain is negative since positive feedback is desired. If $\varphi_{max} > \varphi_{ref}$ the pressure set point should increase. The set point is constrained to the interval 0.158 – 0.165 MPa.

This strategy releaves the operator from specifying a pressure set point, see Shinskey (1978). The choice of valve reference opening is a compromise between energy savings and control authority. If the valve is 100 % open it has no control authority in the positive direction. The value $\varphi_{ref} = 85$ % at Käppala.

The settling time of the pressure reference value is recommended to be 5 – 10 times longer than other settling times in the air production system. Since the air flow rate loops have the longer settling time, 10 – 30 seconds, the

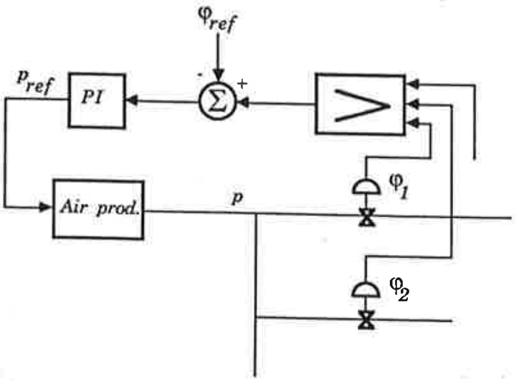

Figure 3. The pressure minimization loop, corresponding to block F in Figure 1.

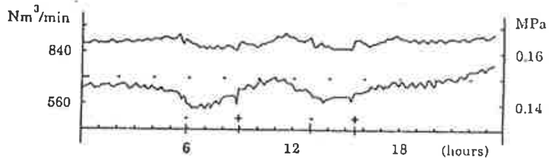

Figure 4. Pressure (upper curve) and total air flow rate (lower curve) during a 24 hour period. Due to the pressure minimization the manifold pressure varies with air flow rate. Compressor starts (+) and stops (−) are indicated.

pressure minimization must not settle much faster than 4 – 5 minutes. The sampling interval was chosen as 2 minutes. Closing the pressure and pressure minimization loops is discussed in the Section on special problems.

Evaluation

Pressure control and minimization is tuned mainly for stability. The great difference in time-scales for the air flow rates and DO dynamics implies that settling times in air flow and pressure loops are not critical. The only requirement is a reasonable margin to the DO control sampling interval of 15 minutes, since the DO control strategy assumes negligible air flow and pressure dynamics. Pressure and total air flow rate during a 24 hour period is shown in Figure 4.

Special problems

This Section discusses a number of problems such as saturations, mode transitions and protection against abnormal DO concentration measurements. The small control space of the compressors amplifies the saturation problems but they would be present irrespective of compressor type.

The two main saturations in the control system are the upper and lower limits of the guide vanes (diffusors) and the throttle valves. They imply saturations in the air production and the air flow to each aerator. The selftuning DO controllers normally have their control outputs, i.e. the air flow rate set points, limited to the range 45 – 160 m^3/min, but the operating range is smaller in reality. The maximum set point change per sampling interval (rate limit) is 7 m^3/min.

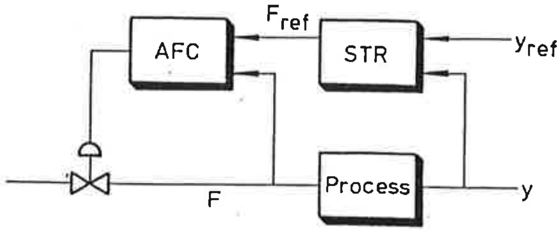

Figure 5. Cascaded self-tuning controller

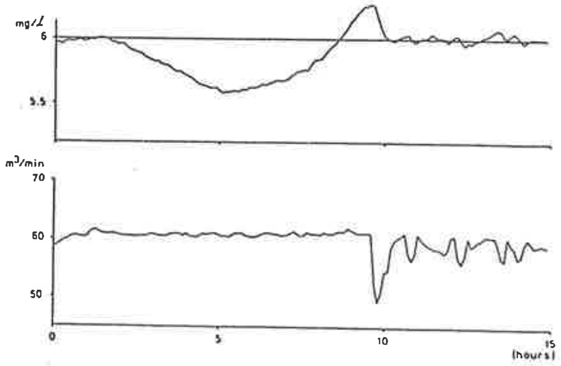

Figure 6. DO concentration (upper curve) and air flow rate (lower curve) during reset windup due to failing throttle valve saturation indication. The air flow remains constant despite a decreasing DO concentration, while the air flow rate set point (not shown) increases to the upper limit. The saturation results in an overshoot in DO and a too high controller gain, giving a noisy output after the saturation has disappeared. No extra compressor could be started automatically.

Throttle valve saturation

A self-tuning controller in cascade with another controller, see Figure 5, creates special problems during saturation conditions. Saturation of the control output of the self-tuner is more easily taken care of internally in the algorithm, see Wittenmark and Åström (1984), but when the cascaded controller saturates, this information must be fed back to the self tuner. Otherwise it will give two types of windup, control output windup due to integral action and parameter windup if the estimation continues, see Figure 6.

These problems are enhanced, since (at least) one throttle valve operates close to saturation. The actual upper limit for the control output from the self-tuner is time-varying and unknown. If the throttle valve saturates, the corresponding rate limit is set to zero and adaptation is switched off. Figures 6 and 7 demonstrate failure and success in this anti-windup scheme using logged data from the Käppala plant. Rundqwist (1985) contains in a number of other suggestions of anti-windup measures.

Guide vane saturation

When the guide vanes (and diffusors) saturate the manifold pressure is controlled by the throttle valves. Closing throttle valves may increase the pressure unless the guide vanes can compensate by closing. Opening throttle valves can similarly create a pressure drop. At lower guide vane saturation the negative rate limit of the DO controllers are set to zero and adaptation is switched off. Upper guide vane saturation is treated differently, see Section 'The compressors', since then a compressor may start. If no compressor can be started the positive rate limit is

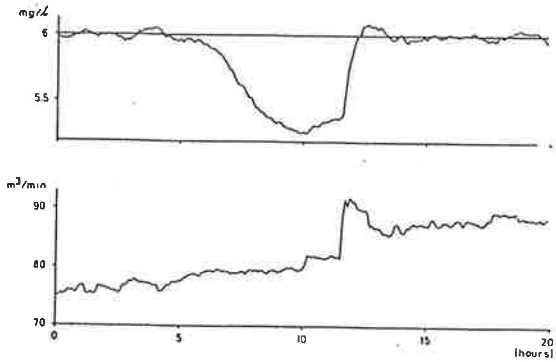

Figure 7. DO concentration (upper curve) and air flow rate (lower curve) during throttle valve saturation where the positive rate limit is set to zero. The saturation starts after 6 h, and the air flow rate remains constant while the DO concentration drops. After 10 h, the saturation disappears temporarily, and after 12 h, when a compressor is started manually, it finally disappears. Since adaptation was switched off the gain is unchanged after the saturation. The overshoot in DO is negligible compared to normal output variations. No extra compressor could be started automatically.

set to zero. Adaptation is switched off in both cases.

The pressure minimization loop contains an integrator. When pressure control is saturated the rate limits of the pressure set point must be set to zero.

Operating modes

The operating personnel may choose different operating modes for the control system. The air flow rate and guide vane (diffusor) controllers indicate their operating mode by logical signals. The signal "Automatic" indicates closed loop control and "Automatic & External" indicates closed loop control using a remote set point. These signals are monitored in order to determine the operating mode of the control program.

EXAMPLE 1

If the manifold pressure is in closed loop control the modes of the air flow rate controllers have the following consequences. If any air flow rate controller is in "Automatic" the pressure minimization operates. If any air flow rate controller is in "Automatic & External" both pressure minimization and DO control (for the selected aerator) operate.

Mode transitions

The self-tuning DO controller updates set point, feedback signal and external control signal (air flow rate) at every sampling instant in manual mode. When the air flow rate controller is switched to "Automatic & External" mode, remote set points are taken from the Novatune. With a sampling interval of 15 minutes this does however not ensure bumpless transfer to automatic mode. The remote set point must be updated with a sampling interval much shorter than 15 minutes.

In the Novatune the self-tuning algorithm may use one sampling interval in open loop and an integer multiple k of this sampling interval in closed loop. The algorithm checks the operating mode using the short sampling interval. Signals are updated in manual mode. A counter is updated and tested in automatic mode. The control algorithm is executed every k:*th* sampling instant. Further, the program can be separated into several tasks, concurrent processes,

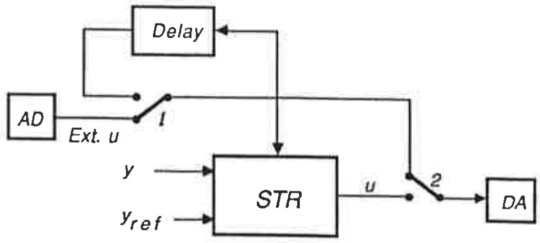

Figure 8. Block diagram describing mode transitions. The switch positions indicate manual mode. The Delay and the AD and DA converters have short sampling intervals while the selftuner has a longer sampling interval.

using different sampling intervals and priorities.

The solution in Figure 8 is used at Käppala to achieve both fast and bumpless transfer to automatic mode The external control signal (air flow rate at present) is updated once per second by the AD converter. In manual mode the external control signal is fed directly to the DA-converter. The open loop sampling interval for the self-tuning controller is 1 minute. The closed loop sampling interval is 15 minutes. When the air flow rate controller is switched to "Automatic & External" mode, the bypassed signal is held constant, by switching switch 1 to the upper position. At next sampling instant for the self-tuning controller, it is still held in manual mode to ensure updating of the external control signal. Then, after 1 minute, switch 2 is switched to the lower position, the self-tuner is switched to automatic mode and at next sampling instant the loop is closed. The transition to manual mode is immediate. Thus the loop is closed within 1 – 2 minutes, and the external set point to the air flow rate controller, from the DA converter, is updated once per second in manual mode.

Inappropriate data is collected by the self-tuner in manual mode because of the difference in sampling interval. To avoid problems, no adaptation should take place in automatic mode until data has been collected using a correct sampling interval. Having $n = \max(n_R, n_S, \ldots)$ where n_R is the number of estimated R-parameters, etc., adaptation must not take place the first n closed loop sampling intervals.

The pressure minimization has a similar problem and solution, since the sampling interval is 2 minutes. When the pressure control (sampling interval 1 second) is started, the initial pressure is used as a constant set point. Then the pressure minimization will start updating the set point within 2 – 4 minutes, i.e. at the second sampling instant.

Large DO changes or signals

Normal load changes to the activated sludge process give slow changes in the DO concentration. Fast changes indicate some type of malfunction, e.g calibration or cleaning of the DO probe, or toxic input to the plant. These changes should not be compensated for by the control system.

When the DO probe is lifted out of the liquid, e.g. for cleaning or calibration, its output signal first becomes maximum which is easy to detect. During cleaning or calibration, the output may change all over the measurement range. It is difficult to make a simple robust test, indicating that 'normal' measurements are received again. When the DO signal exceeds a test limit, a SR flip-flop is set. Then the control output is held constant. The flip-flop is reset by switching off "Automatic & External" mode for the air flow rate controller, which is what the operator should have done in the first place anyhow. DO control is then restarted by switching on "Automatic & External" mode.

If the plant receives toxic compounds, the DO concentration may increase or decrease quickly. If the toxic compounds kill or limit the activity of the organisms, the DO concentration increases, and if the compounds are highly oxidizing they consume almost all the available oxygen. Such DO concentration changes can be larger than 2 mg/ℓ during 10 minutes in either direction. There are two reasons not to compensate these large changes. First, as long as the toxic compounds remain in the aerator, it is almost out of control anyway. Second, trying to compensate would immediately saturate (and possibly upset) the air production system. The fast changes are detected by large control error magnitudes ($> 1.5\ mg/\ell$). Then rate limits of the air flow rate set points are kept small. The DO controllers will slowly catch up the air flow demand and restore the DO concentration to the set point. Adaptation is of course switched off during large control errors.

The compressors

This Section discusses the consequences of limited compressor control space, e.g. a pressure control strategy using 2 different types of compressors, conditions for starting/stopping a compressor and "windup on purpose" in order to handle the discontinuities in the air production. The restrictions in the air production can be eliminated by replacing present compressors by other types with larger control authority. As long as this is regarded as too expensive, 50–100.000 USD each, the control system has to cope with the present equipment. Self-tuning control is used as far as possible and heuristic tricks and fixes are used during non-ideal situations.

The compressors have roughly the same capacity. Thus the air flow unit in the subsequent discussion is "per cent capacity" of one compressor, i.e. 100 % equals the capacity of one compressor. One of the compressors has only on/off control. Three compressors allow 15 % flow reduction each and have fast actuators (guide vanes (GV)). One diffusor-equipped compressor allows 55 % flow reduction, but this actuator is much slower than the guide vanes. The normal demand is 2–3 compressors and 2 is minimum demand. The size of the control space will thus depend on which of the compressors are running and there will be step changes in the air production when compressors are switched on and off. The differences in control speed necessitates a special pressure control startegy. The limitations imply possible windup problems and special tests are required before starting and stopping a compressor.

Pressure control with two compressor types

Pressure control does not run well if all compressors are handled equally. Instead the control operates in different modes depending on the available types of compressors. The three guide vane compressors have fast but small control action, while the diffusor-equipped compressor has slow but large control action. The pressure control strategy is chosen as follows, see Figure 9.

If only one type of compressor is running, i.e. either guide vane or diffusor equipped compressor(s) but not both types, then this type of compressor of course must control the pressure. For guide vane compressors a PI controller (GV-PI) handles pressure control with 1, 2 or 3 compressors. If the diffusor-equipped compressor is running a PID controller (D-PID) is used for pressure control. This loop is considerably slower than the guide vane loop.

When both types of compressors are running, which is the case in Figure 9, the guide vanes are used for

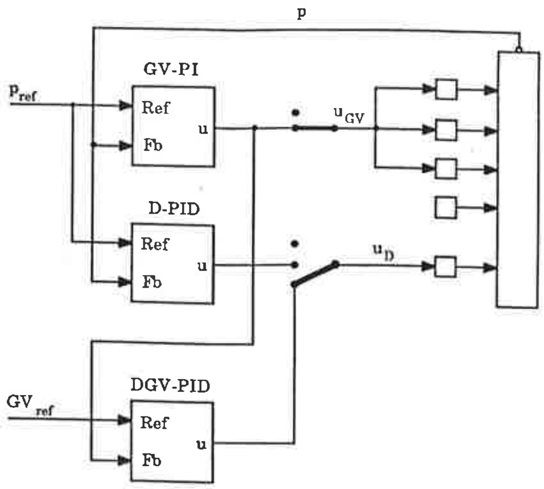

Figure 9. Block diagram of the pressure control strategy using 2 types of controllable compressors. The 5:th compressor has only on/off control. Switch positions indicate pressure and "guide vane position" control.

pressure control (by GV-PI) and the diffusors are used for "controlling the guide vanes". This loop is similar to the pressure minimization loop, using a guide vane set point of 75 %. The loop uses a PID controller (DGV-PID) with negative gain due to positive feedback. To increase speed and avoid stability problems this loop uses the GV-PI output u_{GV} instead of a guide vane position measurement. If the guide vanes saturate and the pressure is outside a pressure dead band, then D-PID is temporarily switched on to speed up the pressure control. It would otherwise take more time before before the diffusors would manage to force the guide vanes out of the saturation.

Pressure minimization is active only when guide vane compressors are in use. If only the diffusor compressor is used for pressure control, the set point is held constant. This is motivated by the (in this case) slow pressure loop.

Windup on purpose

When a compressor is started the increase in air production must be consumed by the aerators. Otherwise a severe pressure rise will occur since the throttle valves may always close to keep the air flow rate at the set point. A consequence is that the set points of the air flow rate controllers must be high enough to allow the increase in air flow to pass the throttle valves, i.e. the set points (which are control outputs from self-tuning DO controllers) must be a certain quantity above the present air flows. This is usually known as *windup*, and must be introduced *on purpose* before starting a compressor.

Stopping a compressor is harmless, since a reduction in air production will not create any pressure rise. The only precaution is that the throttle valves may not close too much before the compressor is stopped, see earlier discussion on throttle valve saturation.

The possibility of windup is introduced only when the pressure control is saturated at the upper limit, since it is only then a compressor may have to be started. Otherwise the positive rate limits of the self-tuning DO controllers are set to zero during upper throttle valve saturation, see earlier discussion.

The difference between the present maximum and the future (after starting a compressor) minimum air flow is computed and divided between the aerators with active DO control and upper saturation. This amount is the required windup per aerator. When the sum of air flow rate control errors exceeds the total required windup, the air flow condition for starting a compressor is satisfied.

DO control errors

Aside from the introduction of windup, the increase in air production after starting a compressor also implies that the DO control errors must be large enough to require the extra air flow produced by starting a compressor. Otherwise the DO concentration quickly will rise above the set point and a compressor stop will soon be required.

Small test limits in DO control errors before starting or stopping a compressor may result in frequent starts and stops of compressors during certain load conditions. Too large test limits may result in no starts or stops at all. Thus the limits must be chosen such that the air flow demand has changed into another "compressor configuration" and is likely to remain there for a while. For safety reasons there is also a minimum DO concentration test limit which results in starting a compressor even if the DO errors are not large enough.

The DO test limit for starting a compressor is computed as "air production increase" divided by a scale factor. The limit will thus depend on the future compressor configuration. The DO test limit for stopping a compressor is computed similarly.

Conditions for starting one compressor

A compressor is started if the sum of DO errors is greater than the test limit *or* the minimum DO concentration is lower than the minimum test limit, *and* the sum of air flow control errors is greater than the total required windup *and* the pressure control is saturated at the upper limit *and* the pressure is lower than 0.162 MPa. Irrespective of other conditions a compressor is started if less than two compressors are running.

Conditions for stopping one compressor

A compressor is stopped if the sum of DO control errors (negative) are less than a test limit *and* the pressure control is saturated at the lower limit *and* at least 3 compressors are running. For security reasons one compressor is stopped if the manifold pressure is greater than 0.168 MPa.

Evaluation

Normally the aerators are well controlled. During saturated air production DO control is deteriorated, but the behaviour is usually acceptable anyhow. If, however, any aerator(s) is (are) in a poorer state due to higher air flow resistance or similar problems, control is severly deteriorated, see Figure 10. In this Figure one of the aerators has the most-opened throttle valve and is therefor always the first aerator to suffer from air production saturation. It takes some time before an enough number of aerators are saturated and meanwhile the DO concentration decreases in the troublesome aerator. Notice that Figures 2 and 10 are both from the same period. The behaviour of this aerator would be acceptable if the compressors had had a large control space.

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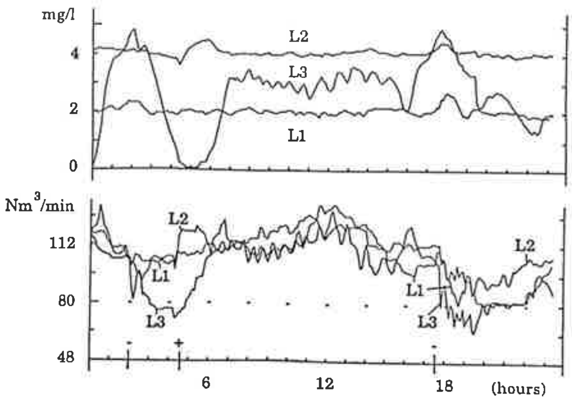

Figure 10. DO concentrations (upper curves) and air flow rates (lower curves) during self-tuning DO control of aerators L1–L3 at Käppala during the same period as in Figure 2. Notice the poor behaviour of aerator L3. Compressor starts (+) and stops (−) are indicated.

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Experiences of Self-tuning Control of an Activated Sludge Process

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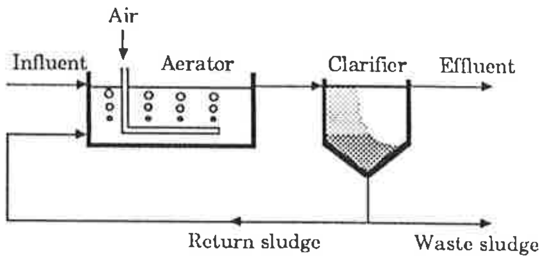
Motivation

Control

Important problems

Summary

Motivation



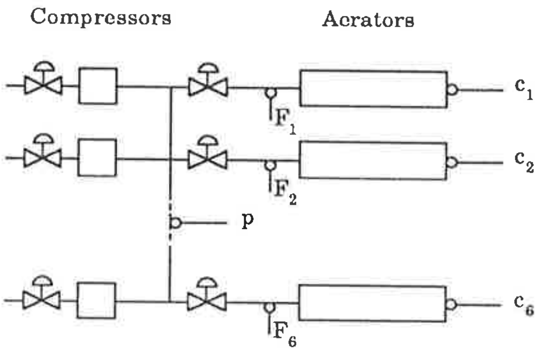
Aerobic biochemical process

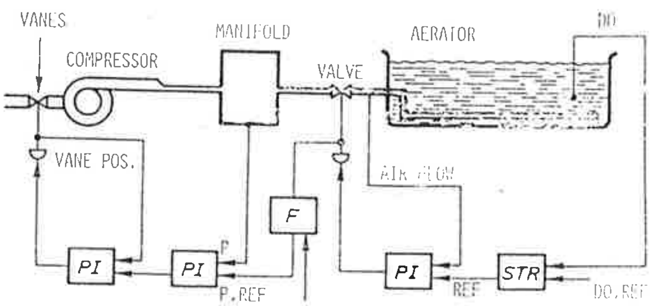
Control

Time constant ≈ 20 minutes

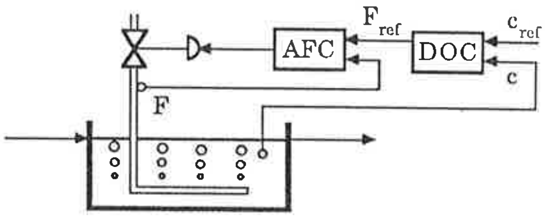
load, parameter variations

Control strategy





Self-tuning control of dissolved oxygen concentration



Dissolved oxygen dynamics (well stirred tank)

$$\frac{dc}{dt} = -a_0 c + (a_1 F + a_2)(c_s - c) - R$$

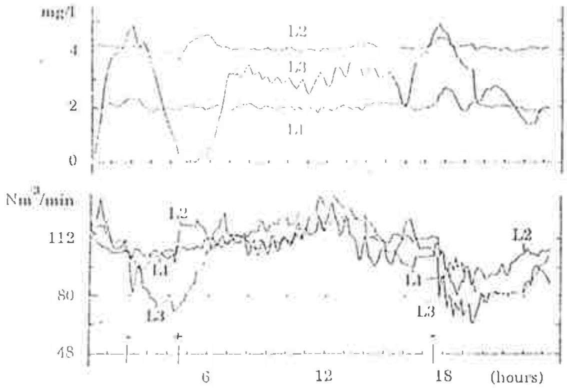
Integrating control law

$$\hat{r}_0 \Delta u(t) = -\hat{s}_0 \Delta y(t) + (1-p)(u_c(t) - y(t))$$

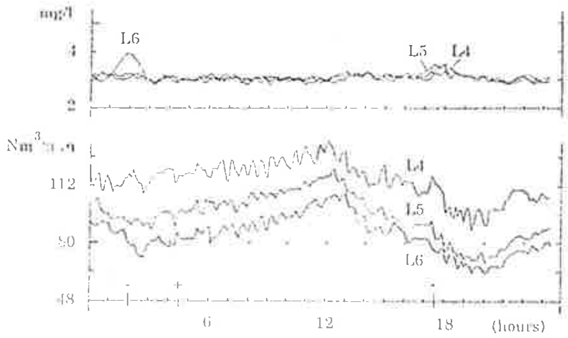
where $\Delta u(t) = u(t) - u(t-h)$

Evaluation of DO control

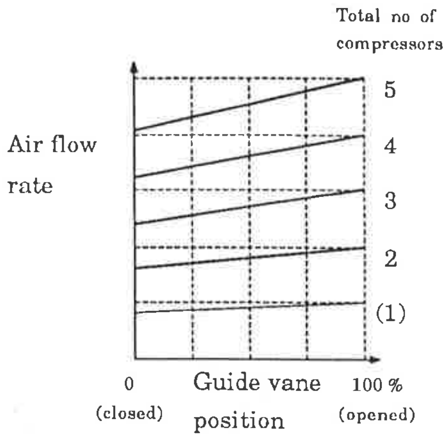
Aerators L1–L3



Aerators L4–L6



The compressors



Conditions for compressor start

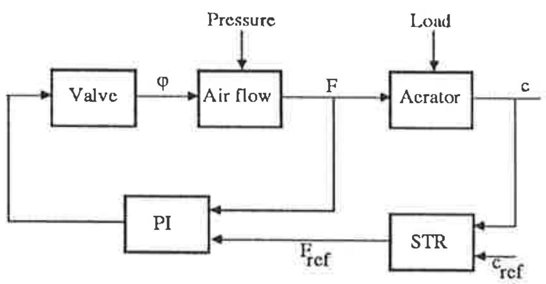
- Extra air flow accepted by controllers

  WINDUP on purpose in DO loop

- Extra air flow required in aerators

Saturations

Example — Throttle valve saturation

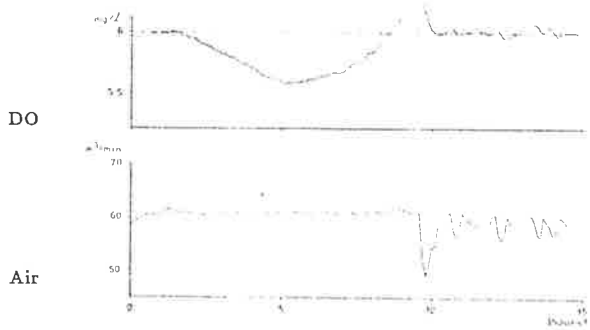


During saturation: adaptation switched off

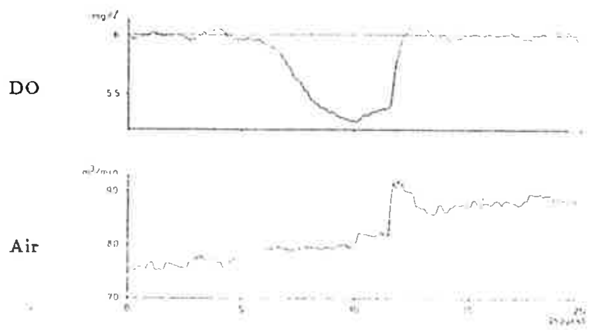
rate limit of F_{ref} set to zero

Upper saturation: compressor may start

windup on purpose



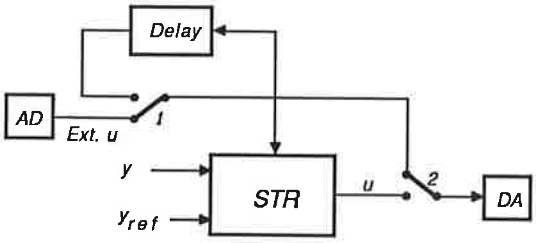
Reset windup   Saturation not detected



No windup

Mode transitions

Example — Starting a self-tuning controller



	Sampling interval
AD, Delay and DA	1 second
STR	1 minute (in manual)
	15 minutes (in automatic)

Large changes in process measurement signal

Reasons:

- Disconnection
- Calibration and/or cleaning of DO probe
- Toxic compounds

Summary

Self-tuning DO concentration control

Pressure control and minimization

Start and stop of compressors

Important problems

Impossible air flow rates

Saturations

Mode transitions

Large changes in process measurement

Pressure control strategy

Operating modes