EVALUATION OF CONTROL PERFORMANCE IN REMOTE MAINTENANCE CENTERS

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Abstract: The number of control loops used in industry is growing continuously and there are problems in keeping them well tuned. During the last decades considerable effort has been placed on developing suitable indices for evaluating control performance. The performance indices developed are often mathematical and background information is required to interpret them. In this paper a set of performance indices appropriate to process monitoring and assessment is presented and case studies from industry are described. Finally, the economic aspects of these indices are discussed.

Keywords: Performance indices, economics, control loops, monitoring loops

1. INTRODUCTION

The number of control loops used in industry is growing continuously and there are problems in keeping them well tuned. However, improved control performance has a considerable effect on variations in end product quality, and thus on the productivity of the plant. In order to ensure highest product quality, it is essential for the automation engineer to maintain control system performance at an adequate level. At the same time the competition between companies keeps increasing, and companies are forced to reduce their maintenance personnel. Nowadays, an automation engineer has to evaluate and control more loops than ever before and it appears that this trend will continue in the future.

Since the number of personnel is being reduced, but the performance has to be improved, companies are using, to an ever-increasing extent, a range of remote expert services for control loop performance evaluation. The evaluation of control loop performance using remote expert centers is usually more cost-effective, since the evaluation of performance often requires steady background knowledge and training. In addition, remote centers have better software and larger control loop databases, thus increasing the chances of success.

In these remote centers the experts are using, in addition to experience, a number of tools for control loop performance evaluation. Sometimes, however, it is difficult for a remote center to justify the usage of their services. The economic benefits are especially difficult to quantify. Performance indices are an ideal way to show that the performance of control loops have indeed been improved. The use of control loop performance measures makes the economic effects of improved control more traceable. Justification is even easier the control loop performance measures can be transformed into economic values.

A short overview of performance assessment is presented in chapter two of this paper, and a set of performance indices appropriate to process monitoring and assessment in remote centres in chapter three. The economic aspects of some of the indices are discussed in chapter four. A description of some control loop monitoring solutions available on the market is given and a new monitoring program developed discussed in chapter five. The testing results of a monitoring program from an industrial case are described in the final chapter.

2. OVERVIEW OF CONTROL LOOP PERFORMANCE ASSESSMENT

During the last decades considerable effort has been placed on developing suitable indices for evaluating control performance. The evaluation methods can be divided into two categories: stochastic and deterministic methods. The most widely studied stochastic indices are those based on using of MVC (minimum variance controller) calculation as a benchmark. The variance of the process output is compared to the smallest, theoretically achievable variance, as initially discussed by Harris (1989). One advantage of these methods is that they require only output data from controlled process and a priory knowledge of the dead time of the process or its estimation. Horch and Isaksson (1999) proposed a modified performance index that is more robust with non-stationary systems. Eriksson and Isaksson (1994) pointed out that a controller with a good MVC index does not necessarily have a good performance with respect to set point changes. Overviews of the research carried out on minimum variance control during the past decade have been presented by Harris (1999) and Qin (1998).

Deterministic indicators are more informative in the case of a sudden load disturbance or a set point change. Various dimensionless indices for set point changes have been proposed in the literature, e.g. by Åström *et al.* (1992). Hägglund (1999) dealt with the rejection of step disturbances and described it by means of the Idle Index. Swanda and Seborg (1999) introduced the dimensionless rise time and the Integral of Absolute Error (IAE) index. Two performance indices, the Absolute Performance Index (API) and the Robustness Index (RI) were introduced by Shinskey (1990).

It is also essential to detect oscillations in the system, caused by valve friction, bad controller tuning or an oscillating load disturbance. These oscillations can be identified by means of autocorrelation functions or spectral analyses (Thornhill and Hägglund, 1997). Horch (1999) demonstrated a method for detecting stiction in control valves based on cross-correlation between process input and output. Hägglund (1995) presented an oscillation detection procedure that involved the calculation of IAE.

3. A SET OF PERFORMANCE INDICES APPROPRIATE TO PROCESS MONITORING

The performance of the control loops are usually considered in three different states: a state with a set point change, load disturbance rejection, and a normal operating state close to the steady-state conditions. Separate indices can be chosen to describe the control performance in these three different cases. In addition other methods, such as calculation of power spectrum and valve monitoring, can be selected for specific monitoring purposes.

3.1 Performance indices for steady state operation

Some indices are suitable for evaluating control performance in the case of a non-varying set point. Oscillations around the set point can be detected by using the method developed by Hägglund (1995), which is based on monitoring the IAE values calculated between consecutive set point crossings of the process value.

$$IAE_i = \int_0^{t_i} \left| y_{pv}(t) - y_{sp}(t) \right| dt \qquad (1)$$

where t_i are the times of successive set point y_{sp} crossing of y_{pv}. If the value of the IAE_i exceeds the predefined value IAE_{lim}, it can be concluded that a load disturbance has occurred. Because the process data are discrete, the IAE_{lim} can be assumed to equal the area of a triangle with a height of $e_{lim}/2$. Thus the IAE_{lim} can be calculated as

$$IAE_{\lim} = \frac{e_{\lim} t_{dis}}{4}, \qquad (2)$$

where t_{dis} is the duration of a single load disturbance that can be calculated if the frequency of the process is known. In an on-line application, the index can be calculated recursively by using the forgetting factor.

$$OSC_i = \gamma \cdot OSC_{i-1} + (1-\gamma) \cdot DIST_i, \qquad (3)$$

where

$$DIST = \begin{cases} 1, IAE_i \geq IAE_{\lim} \\ 0, IAE_i < IAE_{\lim} \end{cases} \qquad (4)$$

Stochastic variations around the set point value can be selected for detection, e.g. by monitoring the integral of the squared error (ISE),

$$ISE_i = \gamma \cdot ISE_{i-1} + (1-\gamma) \cdot \left[y_{pv}(t) - y_{sp}(t) \right]^2 \quad (5)$$

which highlights the largest deviations. These variations may be too short-term to be detected by oscillation detection procedures, but they can be detected effectively with the ISE. The calculation can be carried out on-line by using a recursive algorithm.

An index denoted as ISU can be used as a measure of how much the control action changes. It is similar to the index ISE.

$$ISU_i = \gamma \cdot ISU_{i-1} + (1-\gamma) \cdot [u(k) - u(k-1)]^2 \quad (6)$$

The index will be large if the valve needs to move a considerable amount in order to maintain the set point, and zero when no control action is necessary.

The most popular index is the dimensionless index based on minimum variance control. It describes, how close the actual output variance is compared to the minimum achievable variance, obtained if a minimum variance controller was employed. The reason why we have minimal variance lies in the delay of the plant. The delay *d* prevents the controller from influencing the output immediately. During the first *d* steps the noise passes to the output and the minimum variance is therefore calculated from the first *d* elements of the noise-to-output impulse response of an estimated model.

$$\sigma^2{}_{mv} = \sigma^2{}_a (f_0^2 + f_1^2 + \ldots + f_{d-1}^2) \qquad (7)$$

where f_i are the coefficients of the noise-to-output impulse response, σ_{mv}^2 is the minimum variance, σ_a^2 is the variance of the white noise disturbance.
The output variance σ_y^2 can be calculated from

$$\sigma_y^2 = \sigma^2{}_a(f_0^2 + f_1^2 + ... + f_{d-1}^2 + ...) \quad (8)$$

The performance index based on minimum variance control is

$$\eta = \frac{\sigma_{mv}^2}{\sigma_y^2} \quad (9)$$

In order to calculate this index, the impulse response from the noise-to-output transfer function must be estimated, e.g. using an ARMA model, which can be estimated recursively for online operation. An ARMAX model can also be employed in order to find the time delay *d*.

3.2 Performance indices for set point change occurrences

Monitoring during set point change can be performed during a specific time period, the length of which can be a multiple of the time constant. A response to a step change in a set point value, and the key values that have to be determined from the process measurements in order to calculate the indices, are illustrated in Fig 1.

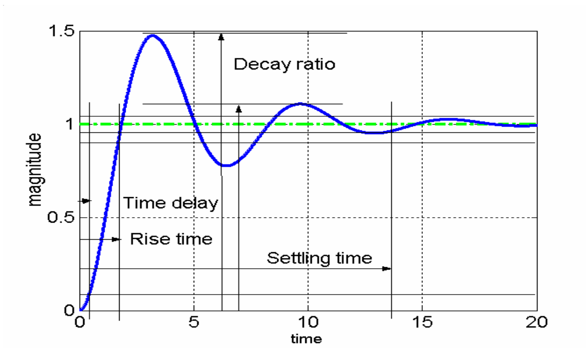

Fig. 1. Response to a step change in a set point.

Oscillations around the set point were observed using the method developed by Hägglund (1995). Contrary to the on-line calculation discussed above, exponential weighting was not applied.

After a step change in a set point, there may be some oscillations before the process value settles down to the steady state. An index can be calculated to describe the size of the overshoot related to the step size by measuring the largest amplitude of the oscillation:

$$AMP = \frac{y_{pv,\max} - y_{pv,\min}}{\Delta y_{sp}}, \quad (10)$$

where $y_{pv,max/min}$ are the maximum and minimum values of the process measurement after a rise time and Δy_{sp} is the magnitude of the set point change.

In order to characterize the rise time and settling time, Åström *et al.* (1992) and Swanda and Seborg (1999) introduced procedures for calculating the normalized indices. In these studies an estimate of an apparent time delay was used to non-dimensionalize the indices for a rise time and settling time. The dimensionless indices can also be calculated by relating the rise time and settling time to an approximation of a time constant τ. The dimensionless indices for a rise time and settling time can therefore be expressed as follows:

$$SPD = \frac{t_{rise}}{\tau} \quad (11)$$

and

$$TIME = \frac{t_{settling}}{\tau}. \quad (12)$$

The oscillation index for a set point change is calculated in the same way as the steady state oscillation index in Eqs. 1,2 and 4 except that the final index is simply

$$OSC = \sum_i DIST_i\,. \quad (13)$$

The OSC index is therefore the number of set point crossings where IAE_i has been larger than IAE_{lim}.

3.3. Performance index for disturbance rejection

Disturbance rejection can be detected by the Idle index. The index is defined by

$$I_i = \frac{t_{pos} - t_{neg}}{t_{pos} + t_{neg}}, \quad (14)$$

where the following procedures are updated every sampling instant:

$$t_{pos} = \begin{cases} t_{pos} + h & \text{if } \Delta u \Delta y > 0, \\ t_{pos} & \text{if } \Delta u \Delta y \le 0, \end{cases}$$
$$t_{neg} = \begin{cases} t_{neg} + h & \text{if } \Delta u \Delta y < 0, \\ t_{neg} & \text{if } \Delta u \Delta y \ge 0, \end{cases} \quad (15)$$

and h is the sampling period.

The index is bounded to the interval [-1,1]. A positive value of I_i close to 1 means that the control is sluggish and negative value of I_i close to –1 is obtained in a well-tuned control loop. The index is calculated only during periods when there are sudden load disturbance, detected by Hägglund idea to compare IAE_i value and predefined IAE_{lim}. Therefore the index should not be taken into advance in case of oscillations.

2.4. Performance index for valve monitoring

Undesirable performance of a control loop may also result from an inadequate actuator sizing, and not only from poor controller tuning. Therefore a saturation index can be used to monitor the valve capacity. The value of the index describes the time t_{vc} that a valve opening is greater than 90 % or smaller than 10 % with respect to the time needed to carry out the set point change. The saturation index can therefore be calculated as

$$SI = \frac{\int_0^\tau t_{vc} dt}{\tau}, \qquad (16)$$

where

$$t_{vc} = \begin{cases} 0, x \in [0{,}1 \ldots 0{,}9] \\ 1, x < 0{,}1 \vee x > 0{,}9 \end{cases} \qquad (17)$$

and x is the valve opening. Values close to zero indicate a correct actuator sizing, and values close to one are a sign of a deficient valve sizing.

4. ECONOMICAL ASPECTS OF CONTROL LOOP PERFORMANCE MEASURES

The performance measures described above are mathematical, and interpretation would be easier if the indices could be transformed into economic values. A benefits analysis method is needed to transform the indices into economic values.

Perhaps the most comprehensive treatment of the benefits analysis process for control systems is Marlin et al (1987). In the method proposed by Marlin et al (1987), the benefits of improved regulatory control have been quantified through variance reduction. When the variance of the process is reduced, the process can be run closer to the constraints.

Indices that correlate with variance can be transformed into economic measures. Such indices include some classical control loop performance measures: Integral of Squared Error (ISE) and Integral of Absolute Error (IAE). In addition, the indices whose calculation is based on IAE or ISE can, in some cases, also be transformed.

Evaluation of the economic aspects can also be based on the methodology introduced by Di Mascio and Barton (2001). The methodology uses a Taguchi framework in evaluating performance properties in economic terms.

The minimum variance index, as described in this paper, cannot be transformed directly into economic measures because the quotient does not have a reasonable physical interpretation. However, the minimum variance criterion has some value as a benchmark, since it can be used to estimate the potential benefits that can be obtained from process control (Muske 2003).

5. PERFORMANCE ASSESSMENT SOFTWARE

A number of vendors are now selling tools for control loop monitoring and process assessment. These include: ABB, Aspentech, ControlArts, ExperTune, Honeywell, Matrikon. Some of them are described here in a nutshell.

5.1 Honeywell Loop Scout™

The most famous product for regulatory performance assessment is Honeywell's Loop Scout™. This solution identifies controller problems by collecting data from the plant, uploading them to the server via the Internet, and analyzing them using benchmarks, and valve and control metrics.

One big advantage of this product is that it uses previous experience in identifying regulatory control performance problems and employing this information to explore new loops, but of a similar type, using a benchmark. Another major advantage is the tight report which classifies the control loops according to the performance quality. This allows prioritizing the problems and directing the efforts at those loops which cause the greatest losses for the facilities. There are some disadvantages: this product is an off-line tool for process performance assessment.

5.2 ExperTune PlantTriage™

PlantTriage continually monitors and analyzes process performance by calculating about 30 measures for every loop. The calculated measures include an MVC-based index, overshoot, normalized IAE, robustness etc. The program uses these measures to identify the loops with the largest payback. These are loops which, when improved, yield the greatest economic return. Other vendors do not implement this kind of online benefit analysis.

5.3 Matrikon Process Doctor™

ProcessDoctor™ is a Matrikon software product available in an on-line and an off-line version. It is designed for identifying poorly performing control loops, diagnosing performance problems, measuring maintenance success and monitoring performance in order to sustain long-term benefits. There is a user-specified tool for data validation and data storing. It is also possible to use a known period of good operations as a benchmark. The service factor, i.e. proportion of time of each controller mode, proportion of time the actuators are at their constraint limit, operator interventions and alarm statistic (number, frequency, duration), are also taken into account. MVC as a benchmark, settling time, autocorrelation function, oscillation index and other indices are used for control performance assessment. There are other tools (based on cross-correlation functions) for interaction analysis of multivariable processes.

5.4 HUT Control Loop Performance Evaluator

The control performance monitoring program developed at Helsinki University of Technology provides a tool to examine the functioning of control loops. Four indices are implemented: a minimum variance index, an ISE-index, a saturation index and an oscillation index. In addition the program calculates a power spectrum of the control loop.

The program was developed using Visual Studio 6.0 software and programmed with Visual Basic. The program works as an OPC client and collects data from an OPC-server at a specified rate calculating the performance indices at certain intervals for each configured loop using Matlab R12.

6. TESTING RESULTS

The monitoring program was tested in Outokumpu Kokkola zinc plant. Production of zinc can be divided in five parts: roasting process, dissolution process, purification process, electrolysis, and casting. The control performance monitoring program tested the loops in the dissolution and purification process. This part of the process included about 450 normal feedback loops, 40 cascade control loops and 50 proportional control loops. The loops selected to be discussed in more detail in this paper describe behaviour of an oscillating loop, a well-tuned loop, and a slow loop.

6.1 Oscillating loop

The control loop describing oscillating behavior is used in the level control of the second of six flotation cells in series in zinc purification process. Based on the output data as described in Figure 2, it can be concluded that the process was quite unstable, oscillation being almost 15%. The oscillation time was approximately 500-1000 seconds. The gain parameter of the controller was 0.8 and the integral time was 300s. From the index values calculated it can be concluded that the program predicts the oscillation of control loop. The values of the minimum variance index are close to zero; the values for the ISE and the oscillation indices are high. In addition the values for the saturation index are zero. The low value of the saturation index indicates that the controller is sized properly.

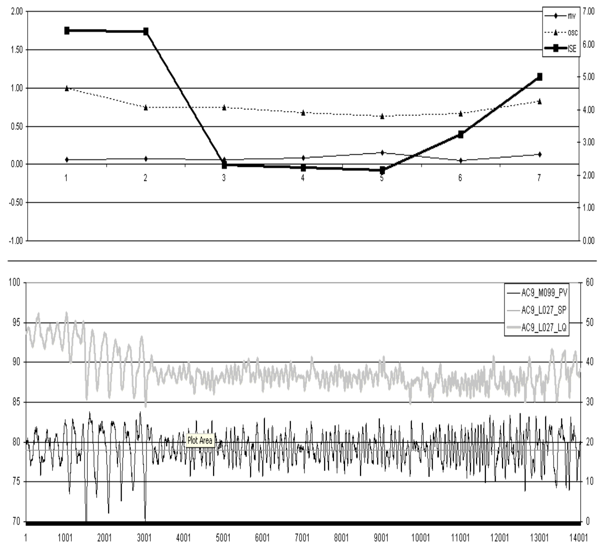

Fig. 2 Performance indices for the oscillating control loop

6.2 Well tuned control loop

The controller loop describing good behavior is used in the level control of tank in an enrichment dissolution process. Based on the output data as shown in Figure 3, it can be concluded that the loop is much faster than the loop above. The specific feature of this controller seemed to be that it was used as a P-controller, because the integral time was set as a high value of 1200s. The gain parameter of the controller was 10.

From the calculated index values it can also be seen that the control loop is well tuned. The values for the minimum variance index, the oscillation index and the ISE index are very good. The values of the minimum variance are high; the values for the oscillation and ISE indices are close to zero. The saturation index values differ from zero but this can be expected since the controller is fast.

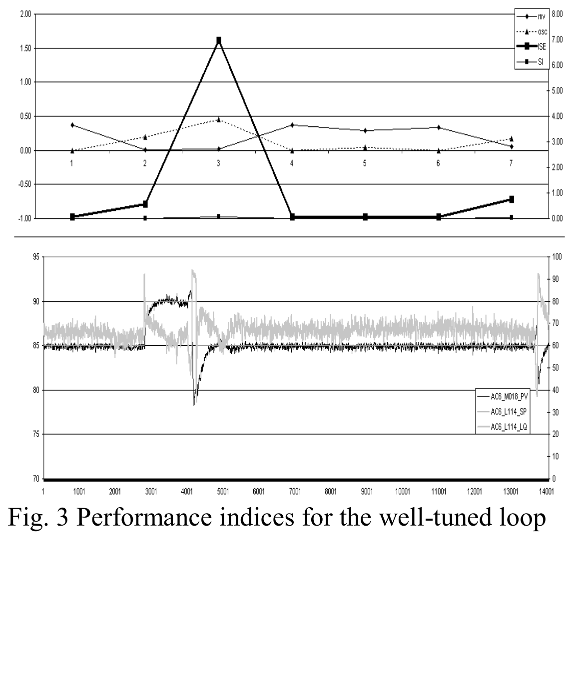

Fig. 3 Performance indices for the well-tuned loop

A set point change at a time of 3000 seconds caused bad values for the minimum variance index, but these can be ignored since the minimum variance index wasn't planned to handle situations of that kind.

6.3 Slow control loop

The controller loop describing the slow behavior is used in the control of the back flow rate of H_2SO_4 to the tank. The loop is otherwise stable but big process disturbances cause big deviations from the set point. The gain parameter of controller was 0.5 and the integral time was 30s. From the index values calculated it also can be concluded that the control loop is slow. The values for the minimum variance and the saturation indices are close to zero, the values for the ISE index are high, and the values for the oscillation indices varied.

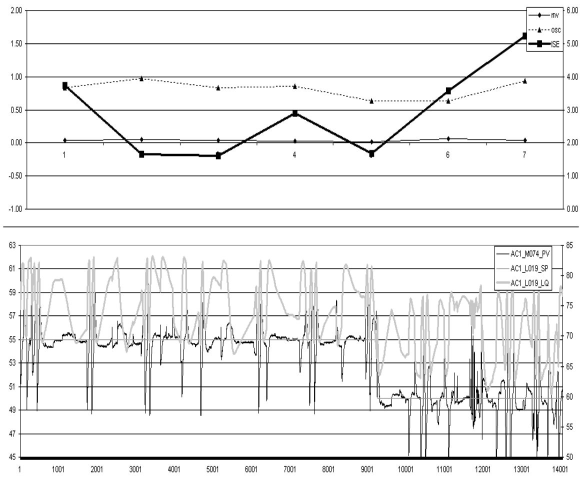

Fig. 4 Performance indices for the slow loop

7. CONCLUSIONS

A set of performance indices appropriate for process monitoring and assessment in remote centers is presented in this paper. The economic aspects of some of the indices are shortly discussed and methods for transforming the measures into economic values are proposed. A description of the monitoring solutions available is presented, and a new remote center monitoring tool that implements some of the indices is developed. The test results of the developed monitoring tool in an industrial case are discussed. The simulations and tests demonstrated that the indices provide the necessary information about the control performance.

In future research, more attention will be paid to the further development of economic aspects in the expert system framework. Methods for transforming the performance indices proposed in this paper will be implemented in a program and tested online.

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