Definition and Verification of the Control Loop Performance for Different Power Plant Types

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Research Project Supported by VGB Power Tech

May 2012
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1 Introduction

The significance of the topic ‘control loop performance’ in process and control engineering gains more and more in importance. The improvement of the control loop performance in power plants enhances their operational safety and the compliance with the increasing requirements from the electrical grid. Furthermore, a high control loop performance is essential for a flexible, efficient, economic and environmentally friendly power plant operation. Therefore, a good control loop performance today has a larger economical relevance for the power plant operators than several years ago, when the main focus was laid on reliability and security.

Final technical approvals for instrumentations, controls and automation systems with regard to control loop performance are generally stipulated by contract for new power plant units as well as for retrofits. In practice however, specifications for the desired control loop performance are inconsistent and mostly based on one single indicator, usually the maximum control deviation. Furthermore, the specification of the required or achievable control loop performance is normally defined without consideration of different operational modes. This can lead to excessively high requirements concerning the control loop performances of new built power plant units or retrofits in respective tenders, which are not achievable in practice.

Within the framework of the VGB research project ‘Definition and verification of the control loop performance for different power plant types’ a systematic methodology for the evaluation of the control loop performance on the basis of meaningful control loop performance indicators was developed and achievable control loop performances were determined. The main aspects of this research project can be concluded as follows:

a) Definition of a practicable set of control loop performance indicators, depending on type and dynamic behaviour of important control loops and requirements thereon,

b) Verification of applicability and significance of defined control loop performance indicators on the basis of real measurements,

c) Classification of achieved control loop performances depending on power plant type, operational mode, control loop and operating mode that are shown in Figure 1, and determination of the best achieved control loop performances (benchmarks),

d) Evaluation of the control loop performance influence on the economic efficiency of a power plant.

Figure 1: Application framework
2 Control Loop Performance Indicators and their Application to the Measurement Data

Control loop performance indicators are measures, which describe how well a control is achieving its objectives. Control loop performance indicators that were defined within the framework of this research project and a methodology for their application to the measurement data are described in the following subchapters.

2.1 Measurement Data Evaluation by means of Moving Time Windows

The length of measurement data sets can strongly influence the results of control loop performance evaluation. In order to compare the evaluation results of data sets of different length, the data are to be evaluated by means of a ‘moving time window’. For this aim the time window $T$ is defined and the indicators are applied to the measurement data over this time window. An example representing this methodology is demonstrated on the basis of exemplary curves shown in Figure 2-a and using the exemplary control loop performance indicator ‘negative overshoot $O_{-T}$’. This indicator is described in detail in subchapter 2.2.

![Figure 2: Measurement data evaluation by means of moving time windows - step 1](image)

In the first step the indicator negative overshoot $O_{-T}$ is applied to the measurement data over the time interval $[t, t + T]$ (see Figure 2-a). In doing so the first value of the negative overshoot $O_{-T}$ is determined for the time interval $[t, t + T]$ as shown in Figure 2-b. Afterwards, the time window of length $T$ is moved by one time sample and the second value of $O_{-T}$ is determined for the time interval $[t_2, t_2 + T]$ (see Figure 3). In this way the time window is moved along the entire curve until the last time window with the time interval $[t_{end-T}, t_{end-T} + T]$ is reached and the entire measurement data curve is evaluated. The achieved values of the negative overshoot $O_{-T}$ for all time windows are shown in Figure 4-b.
Figure 3: Measurement data evaluation by means of moving time windows - step 2
The results of the measurement data evaluation are represented in form of a histogram in Figure 4-c. The histogram demonstrates the percentage distribution of the achieved values of the negative overshoot $O_{-T}$. To create this histogram each determined value of the negative overshoot $O_{-T}$ is plotted on the x axis and its percentage distribution on the y axis. The sum of the percentage distributions on the y axis amounts to 100%.

Figure 4: a) Exemplary measurement data
b) Negative overshoots $O_{-T}$ of exemplary measurement data
c) Percentage distribution of $O_{-T}$ in form of a histogram
2.2 Overshoot

The positive overshoot $O_{+T}$ in the time interval $[t, t+T]$ is the difference between the positive peak value of the controlled variable $M_{+T}$ in the time interval $[t, t+T]$ and the set point value $w$.

$$O_{+T} = M_{+T} - w$$  \hspace{1cm} (2.1)

The negative overshoot $O_{-T}$ in the time interval $[t, t+T]$ is the difference between the set point value $w$ and the negative peak value of the controlled variable $M_{-T}$ in the time interval $[t, t+T]$.

$$O_{-T} = w - M_{-T}$$  \hspace{1cm} (2.2)

The peak-to-peak value $PTP_T$ in the time interval $[t, t+T]$ is the difference between the maximum positive and the maximum negative deviations of the controlled variable from the set point in the time interval $[t, t+T]$. Peak-to-peak value $PTP_T$ in the time interval $[t, t+T]$ equals the sum of the positive and the negative overshoot in the time interval $[t, t+T]$.

$$PTP_T = O_{+T} + O_{-T}$$  \hspace{1cm} (2.3)

Figure 5: a) Exemplary measurement data  
   b-1) Positive overshoots $O_{+T}$ of exemplary measurement data  
   b-2) Percentage distribution of $O_{+T}$ in form of a histogram  
   c-1) Peak-to-peak values $PTP_T$ of exemplary measurement data  
   c-2) Percentage distribution of $PTP_T$ in form of a histogram

It is not meaningful to apply the control loop performance indicators $O_{+T}$, $O_{-T}$ and $PTP_T$ to the measurement data with a permanently changing set point (e.g. the power output set point during the primary control operation). It is meaningful to apply these control loop performance indicators to the
measurement data with a constant set point (e.g. live steam temperature set point, power output set point during steady-state operation or live steam pressure set point during fixed pressure operation). Furthermore, it is meaningful to apply these indicators to measurement data during load changes. Due to this, it is possible to assess the transient response of the controlled variable to the constant set point after the load change. Figure 4 and Figure 5 represent determined $O_+, O_-$ and $PTP_T$ of exemplary measurement data as well as their percentage distribution in form of histograms. The smaller the values of $O_+, O_-$ and $PTP_T$ are, the better is the control loop performance.

### 2.3 Mean Value Deviation

The mean value deviation from the set point $MVD_T$ in the time interval $[t, t+T]$ is calculated by integrating the control deviation $e(t)$ over the time interval $[t, t+T]$ and dividing the result by $T$.

$$MVD_T = -\frac{1}{T} \int_t^{t+T} e(\tau) d\tau = -\frac{1}{T} \int_t^{t+T} (w(\tau) - y(\tau)) d\tau$$ (2.4)

The determined $MVD_T$-values of the exemplary measurement data and their percentage distribution are shown in Figure 6. The closer to zero the values of $MVD_T$ are, the better is the ability of a control loop to keep the actual value at the given set point.

![Figure 6: a) Negative control deviation of exemplary measurement data b) Mean value deviations from the set point $MVD_T$ c) Percentage distribution of $MVD_T$ in form of a histogram](image)
2.4 Integral of Absolute Error

The Integral of Absolute Error $IAE_T$ in the time interval $[t, t+T]$ is calculated by integrating the absolute value of the control deviation over a time interval $[t, t+T]$ and dividing the result by the time span $T$.

$$IAE_T = \frac{1}{T} \int_{t}^{t+T} |e(\tau)| d\tau = \frac{1}{T} \int_{t}^{t+T} |w(\tau) - y(\tau)| d\tau$$

(2.5)

Due to the integration of the absolute value of the control deviation, both positive and negative control deviations contribute to the $IAE_T$. Moreover, small and large control deviations are equally weighted. Figure 7 represents the determined $IAE_T$-values of exemplary measurement data and their percentage distribution.

![Figure 7: a) Absolute control deviation of exemplary measurement data
b) Values of integral of absolute error $IAE_T$
c) Percentage distribution of $IAE_T$ in form of a histogram](image)

2.5 Integral of Squared Error

The Integral of Squared Error $ISE_T$ in the time interval $[t, t+T]$ is calculated by integrating the squared control deviation over a time interval $[t, t+T]$ and dividing the result by the time span $T$.

$$ISE_T = \frac{1}{T} \int_{t}^{t+T} e^2(\tau) d\tau = \frac{1}{T} \int_{t}^{t+T} (w(\tau) - y(\tau))^2 d\tau$$

(2.6)

Due to the squaring down of the control deviation before the integration, large control deviations are stronger penalized than small ones. Figure 8 shows the determined $ISE_T$-values of exemplary measurement data and their percentage distribution.
2.6 Standard Deviation

The standard deviation $STD_T$ is a statistic indicator, which shows how tightly the measurement data are clustered around the mean value of a signal in the time frame $[t, t+T]$.

The computation of the standard deviation in the time frame $[t, t+T]$ is described by the following formula:

$$ STD_T = \sqrt{\frac{1}{N} \sum_{n=1}^{N} (e_n - \overline{e}_T)^2} \quad (2.7) $$

where $N$ is a number of samples in the time frame $[t, t+T]$, $e_n$ represents the sample number $n$ of the control deviation $e(t)$ in the time frame $[t, t+T]$ and $\overline{e}_T$ is the arithmetic mean value of the control deviation in the time frame $[t, t+T]$ defined as:

$$ \overline{e}_T = \frac{1}{N} \sum_{n=1}^{N} e_n \quad (2.8) $$

Measurement data with a bell shaped probability density function can be approximated by a normal distribution or Gaussian distribution. When the data samples are tightly bunched together and the bell-shaped curve is steep, the standard deviation is small. When the samples are spread apart and the bell curve is flat, the standard deviation is large.
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The following conclusions are allowed for normally distributed measurement data (see Figure 9):

- 68.27% of the measurement data are within the range of one standard deviation $\overline{e}_T \pm \text{STD}_T$,
- 95.45% of the measurement data are within the range of $\overline{e}_T \pm 2\text{STD}_T$,
- and 99.73% of the measurement data are within the range of $\overline{e}_T \pm 3\text{STD}_T$.

![Figure 9: Standard deviation of normal distributed signals](image)

### 2.7 Distribution of Deviations

This indicator shows the percentage distribution $PD_{kT}$ of $e(t)$-samples in the time interval $[t, t+T]$ within defined ranges. At the same time $PD_{kT}$ corresponds to the percentage duration of deviations within defined ranges. The number of ranges $k$ is variable. The percentage distribution $PD_{kT}$ is calculated by the following formula:

$$PD_{kT} = \frac{N_k}{N_T} \cdot 100\% \tag{2.9}$$

where $N_T$ is number of $e(t)$-samples within the time frame $[t, t+T]$ and $N_k$ is the number of $e(t)$-samples within the range $k$ in the time interval $[t, t+T]$.

For the demonstration of the control loop performance indicator $PD_{kT}$ five following ranges are defined (see Figure 10):

- Range $[-A;A]$;
- Range $[-B;-A) \& (A;B]$;
- Range $[-C;-B) \& (B;C]$;
- Range $[-D;-C) \& (C;D]$;
- Range $[-\infty;-D) \& (D;+\infty]$

The range $[-A;A]$ is always close to zero and is the range of desired deviations. The larger the number of samples in the range $[-A;A]$ is, the larger is the $PD_{[-A;A]} T$ and the better is the control loop performance. The larger are the control deviations, the larger are the $PD_{[-B;-A) \& (A;B]} T$, $PD_{[-C;-B) \& (B;C]} T$, $PD_{[-D;-C) \& (C;D]} T$ and $PD_{[-\infty;-D) \& (D;+\infty]} T$. 

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Figure 10: Negative control deviation of exemplary measurement data and defined ranges

Figure 11: Ranges and their percentage distribution $PD_{T}$

Figure 11 represents the percentage distribution of the samples in all defined ranges. The first histogram, which includes the percentage distribution of the range [-A; A] shows that:

- 95 to 100% of all measurement data samples are concentrated in the range [-A; A] in 90% of all considered time windows and
- 90 to 95% of all measurement data samples are concentrated in the range [-A; A] in 5% of all considered time windows.

Measurement data samples, which have exceeded the range [-A; A], are distributed in the following ranges [-B;-A)&(A;B], [-C;-B)&(B;C] and [-D;-C)&(C;D]. In these ranges are located from 0 to 5% of all measurement data samples in all considered time windows.

In the histogram including the percentage distribution of the range [-∞;-D)&(D;+∞] are no data, because there are no measurement data samples in this range.

2.8 Actuator Effort

Two control loop performance indicators are defined for the evaluation of the actuator’s wear. These indicators are covered regulating distance $D$ and number of shifts in direction $NSD$. 
2.9 Summary of Control Loop Performance Indicators

The control loop performance indicators, which are described in detail in previous chapters, and their features, are summarized in Table 1.

<table>
<thead>
<tr>
<th>Control Loop Performance Indicator</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive Overshoot $O^+T$</td>
<td>Indicates the maximum positive deviation of the controlled variable from the set point</td>
</tr>
<tr>
<td>Negative Overshoot $O^-T$</td>
<td>Indicates the maximum negative deviation of the controlled variable from the set point</td>
</tr>
<tr>
<td>Peak-to-Peak Value $PTP_T$</td>
<td>Indicates the distance between the maximum positive and the maximum negative deviations of the controlled variable from the set point</td>
</tr>
<tr>
<td>Mean Value Deviation $MVD_T$</td>
<td>Indicates the mean value deviation of the controlled variable from the set point</td>
</tr>
<tr>
<td>Integral of Absolute Error $IAE_T$</td>
<td>Indicates the positive and negative deviations of the controlled variable from the set point and penalizes large deviations as strong as small ones.</td>
</tr>
<tr>
<td>Integral of Squared Error $ISE_T$</td>
<td>Indicates the positive and negative deviations of the controlled variable from the set point and penalizes large deviations stronger than small ones by squaring of the control deviation</td>
</tr>
<tr>
<td>Standard Deviation $STD_T$</td>
<td>Indicates how tightly the measurement data are clustered around the mean value of the controlled variable</td>
</tr>
<tr>
<td>Percentage Distribution $PD_{%T}$</td>
<td>Indicates the percentage duration of deviations within defined ranges</td>
</tr>
<tr>
<td>Covered Regulating Distance $D$</td>
<td>Indicates the distance covered by an actuator</td>
</tr>
<tr>
<td>Number of Shifts in Direction $NSD$</td>
<td>Indicates the number of shifts in direction of an actuator</td>
</tr>
</tbody>
</table>

Table 1: Summary of control loop performance indicators and their features

3 Control Loop Performance Indicators and Control Loops Researched

The meaning and the importance of the defined control loop performance indicators for the researched control loops are described in this chapter.

3.1 Live Steam Temperature Control Loop

The influence of the live steam temperature control loop performance on the power plant efficiency and on the lifetime of thick-walled components was investigated within the framework of this research project:

- **Influence of the average live steam temperature on the power plant efficiency**
  
  The thermal efficiency of a power plant unit depends, among other things, on the live steam parameters. The higher the live steam temperature is, the higher is the efficiency. Thus, a continuous positive deviation of the live steam temperature from its set point leads to efficiency gain and a continuous negative deviation of the live steam temperature from its set point leads to efficiency loss.
• **Influence of the average live steam temperature on the lifetime of thick-walled components**
  The live steam temperature affects not only the efficiency of a power plant unit, but also the lifetime of thick-walled components due to creep damage. Investigations showed that a continuous positive mean value deviation of the live steam temperature from its set point causes lifetime loss and a continuous negative mean value deviation of the live steam temperature from its set point causes lifetime gain. It is to be mentioned that the efficiency loss and the lifetime loss during full load operation is much higher than during part load operation.

• **Influence of live steam temperature fluctuations on the lifetime of thick-walled components**
  Not only average deviations of the live steam temperature from the given set point, but also its fluctuations affect the lifetime of thick-walled components due to creep damage. Positive deviations of the live steam temperature from its set point lead to the lifetime loss. Negative deviations of the live steam temperature from its set point lead to the lifetime gain. The live steam temperature has a nonlinear influence on the lifetime of thick-walled components. Due to this fact the lifetime loss that is caused by positive live steam temperature deviations will be not compensated by negative live steam temperature deviations of the same size and shape.

  Investigations showed that the larger the steam temperature fluctuations are, the larger is the lifetime consumption of thick-walled components due to creep damage. However, the lifetime consumption during full load operation is much higher than during part load operation. Moreover, even large steam temperature fluctuations have only a little impact on the lifetime consumption during low load operation. Therefore, the steam temperature deviations are to be kept as low as possible during full load operation and may be allowed to be larger during part load operation.

  Furthermore, it is to be mentioned that continuous positive mean value deviation of the steam temperature has a stronger negative impact on the lifetime consumption of thick-walled components than steam temperature fluctuations. For example, lifetime consumption caused by a fluctuating steam temperature with deviations of ±10 K is lower than the one caused by the continuous positive steam temperature mean value deviation of 2 K.

• **Live steam temperature influence on the lifetime of thick-walled components during load changes**
  Large live steam pressure changes take place during positive and negative load changes. These large live steam pressure changes lead to large compressive stress load cycles in material of thick-walled components. The larger a load change is, the larger is the compressive stress load cycle. If large steam temperature fluctuations occur simultaneously to the live steam pressure change, then it will lead additionally to a large thermal stress load cycle in the material. The sum of the compressive and of the thermal stress load cycle results in a total stress load cycle, which shouldn't exceed the allowable stress load cycle, in order to prevent lifetime consumption of thick-walled components due to fatigue.

  The compressive stress load cycles cannot be reduced, because the large live steam pressure changes are determined by the operating mode. In contrast, the thermal stress load cycles could be reduced. For this, it is necessary to keep the peak-to-peak value of the live steam temperature during a load change under a permissible limit. This permissible limit has to be determined for each
Chapter 3 - Control Loop Performance Indicators and Control Loops Researched

A set of meaningful indicators was selected for the evaluation of the live steam temperature control loop performance with regard to the described topics. In order to avoid both, the loss of efficiency and the loss of lifetime of thick-walled components, it is very important to maintain the average of the live steam temperature at its set point. For this reason, the control loop performance indicator \( \text{mean value deviation } \text{MVD}_T \) is very important for the evaluation of the live steam temperature control loop performance.

Control loop performance indicators \( \text{distribution of deviations } \text{PD}_k \), \( \text{positive overshoot } \text{O}_{+T} \), \( \text{negative overshoot } \text{O}_{-T} \), \( \text{peak-to-peak value } \text{PTP}_T \), \( \text{integral of absolute error } \text{IAE}_T \) and \( \text{integral of squared error } \text{ISE}_T \) are general control loop performance indicators, which are useful for the evaluation of the steam temperature fluctuations.

Since the influence of the average live steam temperature on the efficiency and on the lifetime of thick-walled components is greater than the influence of the live steam temperature fluctuations, the control loop performance indicator \( \text{mean value deviation } \text{MVD}_T \) is the most important indicator for the evaluation of the live steam temperature control loop performance. For this reason, the importance of this control performance indicator is always higher than the importance of control loop performance indicators \( \text{positive overshoot } \text{O}_{+T} \), \( \text{negative overshoot } \text{O}_{-T} \), \( \text{peak-to-peak value } \text{PTP}_T \), \( \text{integral of absolute error } \text{IAE}_T \) and \( \text{integral of squared error } \text{ISE}_T \). The control loop performance indicator \( \text{peak-to-peak value } \text{PTP}_T \) is very important for the evaluation of the live steam temperature control loop performance during load changes.

Since the live steam temperature influences the efficiency and the lifetime of thick-walled components during different operational modes and operating modes in different way, the importance of control loop performance indicators depends on the operational mode and on the operating mode of the power plant unit. The importance of control loop performance indicators at different operational modes and operating modes is described in the following subchapters.

To evaluate the influence of the steam temperature control loop performance on the wear of actuators, the indicators \( \text{covered regulating distance } D \) and \( \text{number of shifts in direction } \text{NSD} \) are used (see Table 2 and Table 3).

3.1.1 Importance of Control Loop Performance Indicators during the Operating Mode 'Modified Sliding Pressure Operation' and 'Natural Sliding Pressure Operation'

If a power plant unit is operated in the "modified sliding pressure operation" or "natural sliding pressure operation", the live steam pressure set point \( P_{\text{St set}} \) changes depending on load and therefore the importance of control loop performance indicators is affected as follows:

- \( \text{Full load operation} \)

  For economical reasons, the fossil-fired power plants are operated at the highest possible live steam pressure (near the upper limit of the construction material) during full load operation. Therefore, the thermal efficiency and the compressive stress in the material of thick-walled components are the highest. For this reason it is important to keep the mean value of the live
steam temperature during full load operation as closely as possible at its set point and the importance of the control loop performance indicator mean value deviation $MVD_T$ during full load operation is very high.

Besides, the steam temperature deviations should be kept as low as possible. Therefore, such control loop performance indicators as distribution of deviations $PD_{kT}$, positive overshoot $O_{+T}$, negative overshoot $O_{-T}$, peak-to-peak value $PTP_T$, integral of absolute error $IAE_T$ and integral of squared error $ISE_T$ are very important during full load operation.

- **Part load operation and low load operation**
  Due to the decrease of the live steam pressure during part load operation, the thermal efficiency and the compressive stress in the material thick-walled components decrease too. Thus, both the steam temperature deviations and the steam temperature mean value deviation have lower influence on the thermal efficiency and on the lifetime of thick-walled components during part load operation. Therefore, the steam temperature deviations and the steam temperature mean value deviation during part load operation can be allowed to be bigger than during full load operation. Therefore, the importance of control loop performance indicators such as $MVD_T$, $O_{+T}$, $O_{-T}$, $PTP_T$, $IAE_T$, $ISE_T$ or $PD_{kT}$ during part load operation is slightly lower than during full load operation. For the same reason, the importance of these indicators during low load operation is slightly lower than during part load operation.

- **Positive and negative load changes**
  In order to prevent additional lifetime consumption of thick-walled components due to fatigue damage, it is necessary to keep the steam temperature peak-to-peak value during load changes under the limit of permissible steam temperature peak-to-peak value $PTP_{\text{fatigue}}$.

<table>
<thead>
<tr>
<th>Control Loop Performance Indicator</th>
<th>Relevance</th>
<th>Full Load Operation</th>
<th>Part Load Operation</th>
<th>Low Load Operation</th>
<th>Load Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value deviation $MVD_T$</td>
<td>Efficiency, creep damage</td>
<td>★★★★★</td>
<td>★★★★</td>
<td>★</td>
<td>★★★★★</td>
</tr>
<tr>
<td>Distribution of deviations $PD_{kT}$</td>
<td>Creep damage</td>
<td>★★★★★</td>
<td>★★★★</td>
<td>★</td>
<td>★★★★★</td>
</tr>
<tr>
<td>Positive overshoot $O_{+T}$, Negative overshoot $O_{-T}$, Peak-to-peak value $PTP_T$, Integral of absolute error $IAE_T$, Integral of squared error $ISE_T$</td>
<td>General CLPIs</td>
<td>★★★★★</td>
<td>★★★★</td>
<td>★</td>
<td>★★★★★</td>
</tr>
<tr>
<td>Peak-to-peak value $PTP$'s Allowable steam temperature peak-to-peak value $PTP_{\text{fatigue}}$</td>
<td>Fatigue damage</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★★★</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Control Loop Performance Indicator</th>
<th>Considered Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Covered regulating distance $D$</td>
<td>Wear of actuators</td>
</tr>
<tr>
<td>Number of shifts in direction $NSD$</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Indicators for the evaluation of the steam temperature control loop performance, $p_{St\text{-set}} \neq \text{const.}$
3.1.2 Importance of Control Loop Performance Indicators during the Operating Mode 'Fixed Pressure Operation' and 'Initial Pressure Operation'

If a power plant is operated in the operating mode "fixed pressure operation" or "initial pressure operation", the live steam pressure set point $p_{St\ set}$ is constant. As a rule, this set point doesn't change during full load operation and during part load operation. Accordingly, there is no change in the live steam pressure set point during a load change from full load to part load and vice versa. Therefore, the control loop performance indicators $MVD_T$, $PD_{kT}$, $O_{+T}$, $O_{-T}$, $PTP_T$, $IAE_T$ and $ISE_T$ have the same importance during these operational modes (see Table 3).

Generally, the live steam pressure set point is reduced during the low load operation. Therefore, the importance of defined control performance indicators is lower during low load operation than during part load operation (see Table 3). During a load change from full load to low load and vice versa as well as from part load to low load and vice versa there is a change of the live steam pressure set point. Due to this fact, the indicator $PTP_T$ is important during this operational mode (see Table 3). If the live steam pressure set point isn't reduced during the low load operation, the importance of control loop performance indicators will be the same during all operational modes.

![Table 3: Indicators for the evaluation of the steam temperature control loop performance, $p_{St\ set}$ = const.](image)

| Control Loop Performance Indicator | Relevance | Importance | | |
|----------------------------------|-----------|------------|---|---|---|
| Mean value deviation $MVD_T$ | Efficiency, creep damage | ⬤⬤⬤⬤⬤ | ⬤⬤⬤ | ⬤⬤⬤ | ⬤⬤⬤ |
| Distribution of deviations $PD_{kT}$ | Creep damage | ⬤⬤⬤⬤ | ⬤⬤⬤ | ⬤⬤⬤ | ⬤⬤⬤ |
| Positive overshoot $O_{+T}$ | General CLPIs | ⬤⬤ | ⬤ | ⬤ |
| Negative overshoot $O_{-T}$ | | | | | |
| Peak-to-peak value $PTP_T$ | Fatigue damage | ⬤ | ⬤ | ⬤ | ⬤ | ⬤ | ⬤ |
| Integral of absolute error $IAE_T$ | | | | | |
| Integral of squared error $ISE_T$ | | | | | |

<table>
<thead>
<tr>
<th>Abbrev.</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC1</td>
<td>Load change from full load operation to part load operation and vice versa</td>
</tr>
<tr>
<td>LC2</td>
<td>Load change from full load operation to low load operation and vice versa as well as load change from part load operation to low load operation and vice versa</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Actuators</th>
<th>Considered Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Covered regulating distance $D$</td>
<td>Wear of actuators</td>
</tr>
<tr>
<td>Number of shifts in direction $NSD$</td>
<td></td>
</tr>
</tbody>
</table>

3.2 Reheater Steam Temperature Control Loop

On the reheater steam temperature control loop performance the same requirements are made as on the live steam temperature control loop performance. Therefore, the indicators that are selected for the evaluation of the live steam temperature control loop performance can be used for the evaluation of the reheater steam temperature control loop performance (see chapter 3.1).
3.3 Power Output Control Loop

By a power plant operator survey that was conducted within the framework of this research project, it was confirmed that the average power output has an influence on the economical efficiency of the power plant operation. For this reason, the average power output has to be kept as good as possible at its set point. If a power plant unit provides control energy, it is important that the output actual value follows as precisely as possible the given set point.

All control loop performance indicators that are meaningful for the evaluation of the power output control loop performance are summarized in Table 4. The control loop performance indicator mean value deviation $\text{MVD}_{T}$ is useful for the assessment of the power output control loop performance influence on the economical efficiency of a power plant unit. Control loop performance indicators positive overshoot $\text{O}_{+T}$, negative overshoot $\text{O}_{-T}$, peak-to-peak value $\text{PTP}_{T}$, integral of absolute error $\text{IAE}_{T}$, integral of squared error $\text{ISE}_{T}$ and standard deviation $\text{STD}_{T}$ are general control loop performance indicators, which indicate the power output deviations.

<table>
<thead>
<tr>
<th>Power Output Control</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value deviation $\text{MVD}_{T}$</td>
<td>Economic Efficiency</td>
</tr>
<tr>
<td>Positive overshoot $\text{O}_{+T}$</td>
<td>General CLPI</td>
</tr>
<tr>
<td>Negative overshoot $\text{O}_{-T}$</td>
<td></td>
</tr>
<tr>
<td>Peak-to-peak value $\text{PTP}_{T}$</td>
<td></td>
</tr>
<tr>
<td>Integral of absolute error $\text{IAE}_{T}$</td>
<td></td>
</tr>
<tr>
<td>Integral of squared error $\text{ISE}_{T}$</td>
<td></td>
</tr>
<tr>
<td>Standard deviation $\text{STD}_{T}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Indicators for the evaluation of the power output control loop performance

3.4 Live Steam Pressure Control Loop

The influence of the live steam pressure on the power plant efficiency and on the lifetime of thick-walled components was investigated within the framework of this research project:

- **Influence of the average live steam pressure on the efficiency**
  
The thermal efficiency of a power plant unit depends, among others, on the live steam parameters. The higher the live steam pressure is, the higher is the efficiency. Thus, a continuous positive deviation of the live steam pressure from its set point leads to efficiency gain and a continuous negative deviation of the live steam pressure from its set point leads to efficiency loss.

- **Influence of the average live steam pressure on the lifetime of thick-walled components.**
  
  Lifetime consumption of thick-walled components due to creep damage depends on the live steam pressure. The higher the live steam pressure is, the larger is the compressive stress in the material of thick-walled components and the larger is the lifetime consumption.

  Power plants are operated at the highest possible pressure (nominal pressure) during full load operation. Therefore, full load operation is the most critical operational mode with regard to the lifetime of thick-walled components. The live steam pressure and the corresponding compressive stress during part load operation are significantly lower than during full-load operation. Hence, the lifetime consumption during part load operation is significantly lower than during full load operation.
Investigations showed that the continuous positive steam pressure mean value deviation causes additional lifetime loss of thick walled components due to creep damage. The continuous negative steam pressure mean value deviation causes lifetime gain. This effect is the stronger the higher the power plant load is. To prevent the additional lifetime consumption of thick-walled components due to creep damage, the steam pressure mean value shouldn't exceed the steam pressure set point.

- **Influence of live steam pressure fluctuations on the lifetime of thick-walled components**

  Live steam pressure fluctuations as well as live steam temperature fluctuations have an influence on the lifetime of thick-walled components. However, the continuous positive steam pressure mean value deviation influences more negatively the lifetime of thick-walled components than live steam pressure fluctuations.

A set of meaningful indicators was selected for the evaluation of the live steam pressure control loop performance with regard to the described topics. These indicators are summarized in Table 5. The control loop performance indicator *mean value deviation* $MVD_T$ is useful for the evaluation of steam pressure control loop performance influence on the power plant efficiency and on the lifetime consumption of thick-walled components due to creep damage (see Table 5). Control loop performance indicators *positive overshoot* $O^+_T$, *negative overshoot* $O^-_T$, *peak-to-peak value* $PTP_T$, *integral of absolute error* $IAE_T$, and *integral of squared error* $ISE_T$ are general control loop performance indicators, which indicate the live steam pressure deviations.

![Table 5: Indicators for the evaluation of the live steam pressure control loop performance](image)

**3.5 Drum Level Control Loop**

A high drum level control loop performance is important to protect boiler components from overheating and from water entry. The dimensions of drums used in different power plant units typically differ from each other. Therefore, the maximum and minimum permissible drum level control deviations can be also different from each. In order to compare the drum level control loop performances of different power plants, it is reasonable to consider them in percent. In doing so it is distinguished between the positive and negative control deviation ranges. The range from the set point to the maximum...
permissible water level in the drum is the range of positive deviations. The range from the set point to the minimum permissible water level in the drum is the range of negative deviations. Both ranges are from 0 to 100 %. At the same time the maximum permissible drum level steady-state control deviations are to be in the range from 0 to x % and the maximum permissible drum level transitory control deviations are to be in the range from x to y % (see Table 6). Control loop performance indicators positive overshoot \( O^+ \) and negative overshoot \( O^- \) can be used for the evaluation of the drum level control loop performance (see Table 6).

<table>
<thead>
<tr>
<th>Control Loop Performance Indicators</th>
<th>Relevance</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive Overshoot ( O_+ )</td>
<td>Damage of boiler components and of steam turbine due to water oversupply</td>
<td>( 1^* )</td>
</tr>
<tr>
<td>Negative Overshoot ( O_- )</td>
<td>Overheating of boiler tubes</td>
<td>( 1^* )</td>
</tr>
</tbody>
</table>

0...x %  Maximum permissible range for drum level steady-state control deviation
x...y %  Maximum possible range for drum level transitory control deviation

\( 1^* \) The steady-state drum level control deviations are to be kept within the range 0...x % and short drum level transitory control deviations are to be permitted within the range x...y %

**Table 6: Indicators for the evaluation of the drum level control loop performance**

### 3.6 Enthalpy Control Loop

A high enthalpy control loop performance is necessary to guarantee a stable fluid mass flow in the evaporator and to keep the attemperation control valves within the controlled range. Moreover, enthalpy control loop performance influences the quality of the live steam pressure control and of the power output control.

<table>
<thead>
<tr>
<th>Control Loop Performance Indicator</th>
<th>Relevance</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value deviation ( MVD_T )</td>
<td>A stable mass flow in the evaporator, Keeping of the attemperation control valves within the controlled ranges, Influence on the quality of the LS Pressure and PO Controls</td>
<td>****</td>
</tr>
<tr>
<td>Positive overshoot ( O_+ ), Negative overshoot ( O_- ), Peak-to-peak value ( PTP_T ), Integral of absolute error ( IAE_T ), Integral of squared error ( ISE_T )</td>
<td>General CLPIs, Disturbance for steam temperature control loops of following superheaters</td>
<td>***</td>
</tr>
</tbody>
</table>

**Table 7: Indicators for the evaluation of the enthalpy control loop performance**
In order to evaluate the influence of the enthalpy control loop performance on the described points, the control loop performance indicator mean value deviation $MVD_T$ can be used. Control loop performance indicators positive overshoot $O_{+T}$, negative overshoot $O_{-T}$, peak-to-peak value $PTP_T$, integral of absolute error $IAE_T$ and integral of squared error $ISE_T$ are general control loop performance indicators, which can be used for the evaluation of the enthalpy deviations (see Table 7).

4 Control Loop Performance and Power Plant Economic Efficiency

In this chapter the sole impact of the control loop performance on the efficiency of an exemplary lignite-fired power plant unit is demonstrated. This power plant unit has the power output of 300 MW and is operated in the operating mode 'Steam generator in control (Turbine Following)' with initial-pressure operation. A renewal of the I&C system was performed in this power plant unit. The control loop performances that were achieved in the power plant before and after the I&C renewal are shown in Table 8. The deviations of the live steam temperature and of the reheater steam temperature were in the range of ±5.5 K before the renewal. The deviations of the live steam pressure were kept in the range of ±3 bar by means of turbine valve throttling (see Table 8). After the renewal of the I&C system, the steam temperature deviations were reduced up to ±3 K and the live steam pressure deviations remained in the range of ±3 bar without turbine throttling. Due to the improved control loop performance, it was possible to increase the set point of the live steam and the reheater steam temperatures as well as to avoid the throttling losses. Those remedial actions led to the increase of the power plant efficiency along with the improvement of the power plant economic efficiency (see Table 8).

<table>
<thead>
<tr>
<th>Control Loops</th>
<th>State prior to the renewal of the I&amp;C system</th>
<th>State after the renewal of the I&amp;C system</th>
<th>Increase of Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS Temperature</td>
<td>+/- 5.5 K</td>
<td>+/- 3 K</td>
<td>0.038 %-Points</td>
</tr>
<tr>
<td>RHS Temperature</td>
<td>+/- 5.5 K</td>
<td>+/- 3 K</td>
<td>0.020 %-Points</td>
</tr>
<tr>
<td>LS Pressure</td>
<td>+/- 3 bar (With throttling)</td>
<td>+/- 3 bar (Without throttling)</td>
<td>0.010 %-Points</td>
</tr>
</tbody>
</table>

Table 8: Improvement of control loop performance and its impact on the power plant efficiency

5 Evaluation Results of Power Plant Measurement Data

Within the framework of this research project the measurement data of hard coal fired, lignite fired and combined cycle power plant units were collected. In total, the measurement data of fourteen European power plant units were evaluated:

- eight hard coal fired power plant units,
- five lignite fired power plant units and
- one combined cycle power plant unit.

<table>
<thead>
<tr>
<th>h - hard coal fired power plant</th>
<th>b - lignite fired power plant</th>
<th>c - combined cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Power Plant Units</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 9: Power plant units that provided measurement data
An overview of these power plant units is given in Table 9. These power plant units are classified depending on power plant type and power output (see Table 9).

The defined control loop performance indicators were applied to the available measurement data in order to evaluate the control loop performance. To make the evaluation results comparable with each other, the indicators were applied by means of the sliding time window \( T = 60 \text{ min} \). Due to this application methodology it was possible to determine the best and the worst achieved control loop performance as well as its mean for the investigated control loops. The results of the measurement data evaluation were classified depending on:

- power plant type,
- power output of a power plant,
- operational mode,
- operating mode and
- boiler type.

Based on the measurement data evaluation optimization potential was revealed in some power plant units. A feedback regarding the results of the measurement data evaluation and analysis was given to the operators of each participating power plant. Besides, it was shown that the measurement data evaluation by means of different control loop performance indicators provides more significant and meaningful results than the measurement data evaluation by means of a single control loop performance indicator. The results of the measurement data evaluation are described briefly in the following subchapters.

The results of the measurement data evaluation are described briefly in the following subchapters.

### 5.1 Power Output Control Loop

A very good power output control loop performance was achieved in some power plant units that were operated in natural sliding and in modified sliding pressure operation during steady-state and during grid control operation. As for the power output control loop performance during grid control operation, the following can be concluded: the larger the grid influence is, the larger the power output control deviations are.

As for positive and negative load changes it can be seen that the larger a positive or a negative load change is, the larger is the power output control deviation. Generally, power output control deviations during load changes without grid influence are smaller than during load changes with grid influence. Moreover, the larger the grid influence during a load change is, the larger is the power output control deviation.

### 5.2 Live Steam Pressure Control Loop

A very good live steam pressure control loop performance was achieved in power plant units that are operated in modified sliding pressure operation. On the basis of evaluation results it can be seen that the larger the grid influence is, the larger are the deviations of the live steam pressure from the set point. Besides, the fluctuations of the live steam pressure are larger during part load operation than during full load operation.
Generally, a good live steam pressure control loop performance was achieved in power plants that are operated in fixed-pressure operation. However, in some of these power plant units the live steam pressure actual value was on average 2 % larger than the given set point during all evaluated operational modes.

5.3 Live Steam Temperature Control Loop

On the basis of the evaluation results it can be concluded that the live steam temperature control loop performance can be very different not only in different power plant units but also in different tracks. For example, in an evaluated power plant unit with four tracks there was a very good performance of the live steam temperature control loop in two of four tracks. At the same time very large negative mean value deviations of the live steam temperature from the set point took place in another two tracks. For this reason, the live steam temperature control loop performance should be determined for each track individually.

In some power plant units a very good performance of the live steam temperature control was achieved. Based on the evaluation results, it can be seen that the fluctuations of the live steam temperature becomes larger with decreasing load. However, a good live steam temperature control loop performance was achieved in some power plant units even during low load operation.

The average of the live steam temperature was approximately 3 K below the set point in many power plant units during different operational modes. This effect was especially evident during grid control operation. Sometimes, the average of the live steam temperature was up to 35 K below the given set point. This influences negatively the efficiency of a power plant unit.

As for positive and negative load changes, it can be generally concluded that the fluctuations of the live steam temperature become larger during load changes. It is striking that the average of the live steam temperature is often lower than the given set point during negative load changes.

5.4 Reheater Steam Temperature Control Loop

The performance of the reheater steam temperature control loop was often very poor in many power plant units. Large negative mean deviations of the reheater steam temperature from the set point, (up to -50 K) took place during different operational modes. In some power plant units these large negative mean value deviations of the reheater steam temperature took place regardless the operational mode. Due to the fact that the reheater steam temperature is often lower than the given set point, the reheater steam temperature control is often not in operation. Besides, this lead to an efficiency loss of a power plant unit.

In some power plant units, different reheater steam control loop performance was determined in different tracks. For example, large negative mean value deviations of the reheater steam temperature took place in three of four tracks and a good performance was achieved in the fourth track. Therefore, the reheater steam temperature control loop performance should be determined for each track individually.
5.5 Drum Level Control Loop
Drum level control deviations were always within the range of permissible drum level control deviations in all evaluated power plant units.

5.6 Enthalpy Control Loop
Based on the evaluation results it can be seen that generally not very large enthalpy mean value deviations from the set point but large enthalpy fluctuations take place in different power plant units during different operational modes. Besides, the enthalpy fluctuations become larger with decreasing load. Moreover, the enthalpy fluctuations during positive and negative load changes are larger than during steady-state operation.

6 Summary
Within the framework of this VGB research project a methodology for systematic evaluation of the control loop performance was developed. This methodology is based on meaningful control loop performance indicators, which were defined in this project. The applicability and significance of each control loop performance indicator was demonstrated using power plant measurement data. For this, measurement data from different power plants at different operating conditions were collected. Defined control loop performance indicators were classified depending on the control loop and requirements thereon. For this a detailed analysis of several control loops was carried out. Moreover, the influence of their control loop performance on the power plant efficiency, on the lifetime of thick-walled components and on the economic efficiency of power plant operation was investigated. These investigations showed that control loop performance indicators have different importance during different operating conditions. Defined control loop performance indicators were applied to the collected measurement data and control loop performances were determined. The best achieved control loop performances can be used as a benchmark for the comparison of existing power plants, for the assessment of the control loop performance during the commissioning of new control concepts and retrofits, for the establishment of requirements on the control loop performance during the tendering phase as well as for the control loop performance monitoring during power plant operation.