ON-LINE PERFORMANCE MONITORING SYSTEM

for the

400 MW COMBINED CYCLE POWER PLANT

TIMELKAM (Austria)

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Abstract:
Today many expert tools for performance monitoring are on the market, but most of them are too much designed for detailed analysis of some of the key components like the gas-turbine, HRSG or steam-turbine. The need of a performance monitoring tool for combined cycle plant giving the operator clear indications about
- Actual Net power output corrected to reference condition and
- Net efficiency corrected to reference condition
together with actual degradation of the overall net power output as well as net efficiency is explained together with its benefits. Based on this information the operator is able to decide about the best timing for GT compressor cleaning or initiate a detailed performance analysis in case of degradation values beyond certain limits.
This case study presents the practical impact on plant operation and optimization which has been achieved with an On-line Monitoring System, that was implemented by an independent Engineer using 3rd party software tools from SimTech's IPSEpro Plant Operation Suite (POS).
The implementation was done plant specific and was executed on basis of the thermodynamic cycle model which was already used in the earlier project phases. This model covers all elements of the whole power block and automatically runs every 15 minutes. So the operators get detailed information about the actual situation and can plan various optimization tasks (e.g. air filter replacement cycles, compressor wash cycles, etc.) as well as react on any drift of measuring instruments and degradation of various plant components (not only GT but also condenser, cooling tower, HRSG elements, pumps, etc.).
1 INTRODUCTION

Gas fired combined cycle power plants are today the most efficient thermal power plants with efficiencies between 58 and 60%. Since the influence of the efficiency (fuel cost) is the major contributor to the cost of electricity (approx. 70%) huge efforts are done in the design of these power plants in order to look for every 10\(^{th}\) of percent efficiency improvement, but these figures are just valid at the beginning of commercial operation (PAC) when the plant is in a so-called “new and clean condition”. For the owner of the power plant, of course, the average performance data (output and efficiency) will count and not those just at the starting point. The question is, what can be done by the operation and maintenance crew, do they look as well for every 10\(^{th}\) of percent in efficiency and does the operator have a chance without an adequate performance monitoring system to optimize performance (minimize degradation)?

Can we give an answer to the following questions?

- What is the actual degradation and is it within a normal range?
- What is the average output and efficiency at the design point over the first 10-15 years of the power plant?
- Do we have some benchmark figures to compare our plant with other comparable power plants?

2 PLANT DESCRIPTION

2.1 Location

Timelkam power plant is located in the middle of the province Upper Austria. Energie AG - a major Austrian utility supplier – currently operates two power generating units, a biomass power plant with 15 MWel and up to 17 MWth and a 400 MWel combined cycle power plant. The Electric power is fed into the public 110 kV power grid while co-generated heat - in the form of hot water - supports the local district heating network in the area Timelkam - Vöcklabruck - Lenzing – Regau.

The combined cycle power plant is a subsidiary of two partners, the Swiss Groupe E and Energie AG Kraftwerke GmbH.
2.2 Technical data of the 400 MW Combined Cycle Power Plant

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial operation</td>
<td>end of 2008</td>
</tr>
<tr>
<td>Fuel</td>
<td>natural gas only</td>
</tr>
<tr>
<td>Net Power Output</td>
<td>408 * MWel</td>
</tr>
<tr>
<td>Net efficiency</td>
<td>58.2 * %</td>
</tr>
<tr>
<td>Co-generated heat</td>
<td>up to 100 MWth</td>
</tr>
<tr>
<td>Total efficiency</td>
<td>up to 70 %</td>
</tr>
<tr>
<td>Load range</td>
<td>25 – 100 %</td>
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<tr>
<td>Operation</td>
<td>daily cycling or low load during night time</td>
</tr>
<tr>
<td>NOx-Emission with/without SCR</td>
<td>≤ 20/25 mg/Nm³</td>
</tr>
<tr>
<td>CO-Emission</td>
<td>≤ 35 ** mg/Nm³</td>
</tr>
</tbody>
</table>

* at design point in condensing mode on grid terminals
** at base load

2.3 Description

The Timelkam combined cycle power plant (short CCPP) went into operation at the end of 2008 in order to meet the rising energy demand in Austria and Europe, to modernize Energie AG’s power generating portfolio and to ensure co-generated heat production to support the local district heating network in the area of Timelkam – Vöcklabruck – Lenzing and Regau.

Based on the actual gas turbine technology of the supplier Siemens the CCPP reaches a net power plant output of 408 MWel and a net efficiency of 58.2% in condensing mode on the high voltage side. Including a thermal heat output of up to 100 MWth the total fuel utilisation rises up to more than 70%. The CCPP is equipped with a selective catalytic reactor (SCR), so we achieve less than 20 mg/Nm³, based on dry exhaust gas with 15% residual oxygen content.

With this modern plant technology a specific NOx-reduction of approximately 90% was achieved, compared to the previously operated, and in the meantime closed, coal fired power plant.

The CCPP is equipped with the latest components of modern power plants. The heart is the proven gas turbine (GT) SGT5-4000F with approximately 280 MWel. The hot exhaust gas of the gas turbine is used for steam production in a triple pressure/reheat heat recovery steam generator (HRSG). This HRSG is of the natural circulation type with a vertical exhaust gas flow through the boiler. At the end of the HRSG a condensate preheater with an integrated district heat exchanger is situated. The steam produced in the HRSG drives a two-casing
steam turbine (ST) SST5-5000. The ST is equipped with two bleedings to supply steam to the two district heating exchangers.

The electrical power is produced in the hydrogen-cooled generator (Gen) of the Siemens SGen5-2000H-type, which is situated between the GT and the ST, called single-shaft configuration. The GT is rigidly coupled and the ST is coupled via a self-shifting and synchronizing couple.

![Aerial view of the power block](image)

Fig. 2-1 Aerial view of the power block

A special feature of the plant is the large load range from 25% to 100% load, allowing the owner a great flexibility to vary the electricity production according to market needs.

In order to be able to operate the plant only depending on the electricity price, also during the heating season, the interest was great, to achieve a maximum decoupling from electricity and heat production. This ultimately led to the decision to add a district heating storage tank. Therefore an existing oil tank was converted into a hot water tank by Energie AG Kraftwerke GmbH.

Various accumulator technologies were investigated and an atmospheric storage was the preferred variant due to the lower investment costs. The accumulator has a volume of 20,000 m³ and a capacity of 600 MWh with a un- and uploading gradient of approximately
60 MW. The storage capacity lasts for a weekend during spring and autumn and one night during cold winter days.

With this plant configuration best availability, lowest emissions and a maximum of operation flexibility is achieved.

Fig. 2-2 Simplified process flow diagram
3 OPERATORS BENEFITS

The benefits of having a plant performance monitoring tool are manifold and it will support the operation- and maintenance crew to optimize the overall performance of the CCPP e.g. with finding the optimal intervals for on- and off-line washing as well as changing air intake filters and to detect in a quite early stage some malfunction of the plant like wrong instrument-signals etc.

3.1 GT off-line washing

An off-line washing initiates cost as well as it requires time to perform it. Additionally after an off-line washing at the plant re-start the GT starting-reliability can be affected. This can occur mainly at bad ambient condition (e.g. cold and wet weather) because of not proper drying possibilities of the GT igniter, but as well due to a mal function of a few of the 24 igniters.

An evaluation of these negative aspects versus the benefits (higher performance) and finding the right timing is only possible with a corresponding performance monitoring tool.

3.2 GT on-line washing

An on-line washing initiate as well cost due to the required operating fluids (cleaning-, antifreeze fluids and deionat) as well as due to operational requirements since the CCPP load during an on-line washing needs to be reduced to 80% load.

The benefits from an on-line washing in average are clearly lower than those from an off-line washing and without a performance monitoring tool the operation crew mostly don’t see any performance benefits and consequently it’s very difficult for them to find out the right cleaning intervals.

3.3 Exchange of GT air intake

The decision to ex-change the filters (moisture separators, pre- and fine filters) at the point in time when the maximum allowable pressure drop is achieved, or already at an earlier stage due to performance issues can be just evaluated with the help of some tool. A performance monitoring system is well suitable for this task.
3.4 Operational optimisation

Under certain conditions (part-load, low ambient conditions etc.) it can make sense to manually switch off one of the cooling water pumps as well as to reduce the fan speed of some of the cooling tower cells and therefore improve the overall efficiency of the CCPP.

Such kind of operational optimization can be done by the operation crew only with the support of an adequate performance monitoring tool.

3.5 Early detection of wrong or drifting signals

In cases where signals starting to drift (what happens in reality from time to time) and those measurement going into the TIT (GT firing temperature) calculation it will impact the overall plant performance (output and efficiency). Such kind of failures can be detected in most of the cases in a quite early phase due to abnormal trends in the actual degradation and then consequently get analysed with the help of available thermodynamic models.

3.6 Supervision of the measured performance values (output and efficiency) after GT maintenance

In case of Timelkam there is a maintenance contract in force with the OEM (Siemens) with corresponding performance guarantees. Based on this contract the plant output as well as the efficiency will be periodically measured. In order to check these measured figures a thermodynamic model can support the operation crew and additionally based on the trend record from the performance monitoring tool the data plausibility can be easily shown.

4 SPECIFICATION

In a Combined-Cycle Power Plant (CCPP) and especially on the Gas-Turbine right from the beginning of commercial operation (at the time of plant performance test where the plant is normally said in “new and clean condition”) degradation on power-output as well as on efficiency will occur resulting in a reduction of the net power-output and net efficiency compared to the original guarantee values “new and clean”.

The root causes for degradation are manifold (GT compressor-fouling as main cause, fouling of GT air intake filter, fouling of GT turbine part, wear and tear, fouling of HRSG etc).
We have to distinguish between the two values

- Non-recoverable degradation (mostly value after GT off-line washing)
- Actual degradation

The most important figure is the average of “actual degradation” over the time, which is the base for the determination of the cost of electricity and will and cannot be guaranteed from the EPC (OEM) supplier.

![Graph showing degradation factors over time](image)

**Fig. 4-1 Expected non recoverable CCPP degradation of power-output and efficiency as per "Combined-Cycle Gas & Steam Turbine Power Plants" 3rd Edition, Rolf Kehlhofer et al., PennWell 2009**

Examples of guarantees from the OEM respectively from the O&M contractor:

- Degradation prior and after HGPI hot gas path inspection or MO major overhaul for power-output and efficiency or
- Degradation curve after GT-off-line cleaning as shown in

![Degradation curve](image)

**Fig. 4-1**

### 4.1 Visualization of the Actual CCPP-Degradation

In order to support the operator in his daily supervision of the plant it is recommended to install in the control room and adequate performance monitoring tool with a visualization of the “actual degradation of the power-plant”.

Without such a visualization it is not easy respectively almost impossible for the operators to monitor the actual degradation and see the results of on-line and off-line washing of GT compressor etc, due to the fact that even a constant full-load over a few days the net-power output is not constant and can vary over 24 hrs in case of a 400 MW CCPP of around 20 MW due to

- Ambient air temperature variation
- Ambient pressure variation and
- Air humidity variation
<table>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>6 a.m.</td>
<td>16</td>
<td>92</td>
<td>966</td>
<td>399</td>
</tr>
<tr>
<td>10 a.m.</td>
<td>20</td>
<td>75</td>
<td>967</td>
<td>389</td>
</tr>
<tr>
<td>12 a.m.</td>
<td>21</td>
<td>67</td>
<td>966</td>
<td>386</td>
</tr>
<tr>
<td>6 p.m.</td>
<td>23.5</td>
<td>50</td>
<td>964</td>
<td>380</td>
</tr>
<tr>
<td>10 p.m.</td>
<td>17</td>
<td>87</td>
<td>965</td>
<td>396</td>
</tr>
</tbody>
</table>

Table: Full load variation example over 24 hrs

Based on this table it’s clearly visible that the operator cannot monitor the actual degradation respectively changes/trends of degradation over a certain time because of continuously changing output figures.

### 4.2 Specification / requirements for a CCPP Performance Monitoring Tool

The most important functions of such a tool are:

1. To calculate (on-line) the actual figures for net-power output and net efficiency back to a clear dedicated reference point (e.g. correction on air-temperature, ambient pressure, humidity and maybe some other figures in case of cogen-plants)
2. To visualize the actual degradation (deviation to the “new and clean values”) over the time
3. To archive all these figures
The Visualization over the time (in function of OH/EOH) is as shown in a simplified picture in Fig 4.2

![Fig 4-2: Typical degradation (output and efficiency) over the time as function of OH/EOH](image)

5 IMPLEMENTATION

The implementation according to the specification mentioned in Chapter 4 has started (and is still ongoing) as "TOMs - TimelkamOnlineMonitoring-System" as follows:

5.1 Physical model

The model (for heat balance off design calculation) was started to be developed when the client had defined Siemens as the EPC contractor for the power island. So it was accompanying the project on the owner side throughout the whole design, construction and test phase including performance tests before it was used as base for the on-line monitoring model.
5.1.1 On-line aspects

For the purpose of on-line monitoring, the model (Fig. 5-1) had to be enhanced regarding convergence by implementing special control structures which were not necessary when it was used manually, since the user could change the setting structure in specific cases (e.g. turn on and off anti-icing subsystems depending on compressor inlet air dew point). Also some automatism for values as they are calculated by the DCS or gas turbine controller (e.g. limits of operation, OTC (outlet temperature, corrected) set-point, etc.) had to be included into the model.

The size of the actual mathematical system of equations of the standard model is 5419 equations and variables, the validation model consists of about 11300 equations and variables, about 300 measured values and the level of redundancy is around 170.
5.1.2 Model library

To overcome the hurdles of on-line model convergence, a plant specific version of the model library was created with the "Model Development Kit" MDK of the IPSEpro program suite (Fig. 5-2), based on SimTech's Advanced Power Plant Library APPlib.

![Fig. 5-2 IPSEpro Module Structure](image)

5.1.3 Model development process

- Creation of the design point model based on OEM's guarantee point heat-balances
- Creation of mapping information between DSC Tag-IDs and model variables for automatic data transfer
- Calibration of model based on performance run data and handling inconsistencies by:
  - adapting model structure or settings
  - adapting mapping information
  - creating measurement adjustment information
- Deriving off-design model with component characteristics
- Checking off-design model manually on steady state operation datasets and handling inconsistencies as mentioned above
- Running model automatically on a large amount of steady state datasets and checking convergence rate and model output
- Optimising convergence and accuracy if necessary
- Release of the model for real-time use
Following these steps consequently results in a very deep knowledge about the plant's behaviour which was then implemented into the physical model.

5.2 System design

As the Power Plant Timelkam is not equipped with a dedicated SCADA system (Supervisory Control And Data Acquisition), the On-line Monitoring Tool has to be connected to the DCS (Distributed Control System, in this plant a Siemens T3000) directly by an OPC read-only connection.

5.2.1 Data acquisition

The primary solution was to use third party OPC-DA client software able to bring the actual measuring data of more than 400 data points into the TOMs database. Due to late availability of a reliable OPC connection there were more than 2 years of historical data available in the DSC. The decision was made to implement an OPC-HDA access to the historical DCS data in order to recover the valuable plant operation data.

5.2.2 Data storage

According to the client’s request and based on site standard, all data are stored in a MySQL database running on the same server as the simulation software for the physical model. As the application is qualified as "non-mission-critical", redundancy of the database is not implemented.

5.2.3 Pre-processing

The usual steps for data pre-processing are executed individually for every timeslot (which is 15 minutes) and for each measurement value.

5.2.4 Processing dataset

Each dataset that has been prepared in such manner and fulfils the requirements for a specific physical plant model is then processed in the simulation service PSServer of the IPSEpro Plant Operation Suite with one of the following solvers:

- Standard (Newton based): For well-defined models
- Optimiser (Neuronal and Newton based): For multi-dimensional optimisation problems of free operator parameter (in Timelkam not implemented yet)
- Validation (Newton based): For Data Validation and Reconciliation of over-determined systems - similar to VDI 2048 "Uncertainties of measurement during
acceptance tests on energy-conversion and power plants Fundamentals" (in Timelkam currently under implementation)

5.2.5 Visualisation
In order to visualise the main results "power and efficiency degradation", some other simulation results like effect of filter fouling and further quarter hour average operation values of common interest, a web-browser based graphical user interface (GUI) was implemented and is accessible by a dedicated terminal in the central control room.

5.3 Hardware implementation

All software necessary for the operation is running on a single Windows(R) based server as the application is qualified as "non-mission-critical", as shown in Fig. 5-3. With state-of-the-art multi-core processors it is possible to get results of more than 10 model variations, including 2 validation runs, within less than 10 minutes on average; so 15 minute time slots can be calculated almost in real time.
6 RESULTS

Creating and using a physical model able to run steady state normal operation conditions of the plant fully automatically provides a deep and complete understanding of the plant's behaviour and limits.

6.1 Degradation in the first 3 years of operation

![Timel kam CC Degradation](image)

Fig. 6-1 Power and efficiency degradation over EOH during the first 3 years of operation

Fig. 6-1 shows the degradation of the power plant until March 2012 with the actual model version (not using data validation and reconciliation yet).

In the first years, off-line washing was performed only once a year (orange lines). Therefore, the effect in power recovery was quite large. The degradation after off-line washing is very close to expected degradation (dashed lines).

Degradation that is caused by air intake filter fouling is not included in this graph (see 6.4).

6.1.1 Efficiency degradation

The model uses data from three gas flow meters and the lower heating value as transmitted from the on-line chromatograph. The gas flow meters' internal conversion is based on a constant standard gas composition. Therefore, their output in standard-m³/h, which is actually the only available signal, is influenced by deviation of the actual gas fractions. This may
result in errors of the calculated efficiency as shown by the spikes at the end of summer 2010 and 2011 (10,000 to 11,000 and 16,000 to 18,000 EOH), reaching up to 2% influence on the efficiency values.

The visualisation suggests an efficiency trend of 1% over 3 years (beginning at 4000 EOH) with available data, showing a slight influence of compressor off-line washing. However, varying gas composition might also interfere with this trend.

6.1.2 Power degradation

In the large scale, between compressor off-line washings there is a clear trend with approx. 2% degradation per year. The portion recoverable by compressor off-line washing is about 1.3% per year. So the non-recoverable power degradation remains in the range of 0.7% per year.

6.2 Off-line compressor washing

As an example, on Fig. 6-2 you may see the result of the off-line compressor washing on 17.9.2011 at 16,809 EOH in the tools standard output format as an almost 4 MW rise of the blue line. The efficiency output line is not significant because this was a period of heavy changes in gas composition as explained above.
6.3 On-line compressor washing

The tool does not show recognisable changes in degradation due to on-line washing actions. This may be explainable by the frequent washing actions up to now (every 1 to 3 days of operation). The resulting improvement is too small in relation to measurement and model noise.

![Fig. 6-3 Exceptional on-line washing effect](image)

There was an exception during the cold period of Feb. 2012, when on-line washing was not executed for 555 EOHs (which was the longest period so far) because the ambient air temperature was below -10°C for 18 operating days. Therefore, the result of the first washing after this period on 14.2.2012 at 15:15 (at 20107 EOH) was remarkable about 5 MW in power and approx. 0.1% in efficiency as shown in Fig. 6-3.

6.4 Air filter replacement

The gas turbine is equipped with coalescer, coarse filter and fine filter, which can be replaced individually.

The measured value of the entire filter system's pressure loss is shown in the DCS, but this value’s relation to possible power increase in case of filter replacement is not clear for the maintenance crew, as it depends on ambient and other conditions.
The tool executes an alternative model simulation run with the actual plant properties except for those of the air filter which are set to "new and clean" for every time step and indicates the influence of the filter deposits on power and efficiency as graphically shown in Fig. 6-4.

![Degradation due to air filter fouling](image.png)

In January 2011, there was an unexplainable reduction of the differential pressure in the measurement values. Without correction the filters appear as 0.5 MW "better than new" in the following time period.

Note: Only the coalescer had to be replaced up to now.
7 SUMMARY – OUTLOOK

Today there are already many performance monitoring tools available but due to various reasons they will or cannot be used and that is one of the reasons why we cannot answer the questions given in the introduction.

Some of the installed or commercially available tools are either too simple (just showing very rough trends) or mostly tools for experts and not easy to handle (e.g. GT performance monitoring, HRSG performance monitoring or ST performance monitoring). Such tools can be used eventually in a 2nd step if the operator gets indication from the overall plant performance monitoring that something is not within the normal range.

In the case of Timelkam we are on the right way with the described and installed performance monitoring tool (as shown in chapter 6) to get the expected benefits. Of course as explained earlier the underlined on-line thermodynamic model to recalculate all full-load case (with/without district heating, with/without air preheating for anti-icing etc) back to reference condition is quite complex and is together with the correct signals the most important part to achieve the specified results.

Part-load operation is not integrated (means will not be calculated back to full load reference condition) since it will always be a very time limited operation case.

With the help of the installed performance monitoring tool the operation crew having now a tool to get clear improvements in the operation of the plant and consequently the owner will benefit with an improvement in the economy due to better performance.