Expert Systems – Smart Solutions for Power Plants

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1. Abstract

Power Plants in almost all regions of the world face certain challenges. In some areas like Europe a development to a bigger share of renewable energy production forces the conventional plants to operate in a much more flexible way than ever before. Whereas in other regions like Asia a high electricity demand forces operators to strive for highest availability and maximum production.

In order to face today's challenges, to ensure a timely and quick response and to seize opportunities the operation of power plants needs to be supported by adequate tools. These tools can help operators and engineers by

- providing a reliable foundation for further calculations (e.g. advanced data reconciliation)
- monitoring, processing and detecting relevant data and events
- optimizing parameters of the combustion

The support of adequate tools in power plants enables operators to reach goals like higher efficiency and availability, timely mitigation of damages or better combustion.

The paper and presentation will show examples of such tools and applications.

2. Smart Solutions for Power Plants

Nowadays, power plants in all regions are facing an increasingly difficult economic environment. Therefore it is becoming all the more important to ensure a high availability of plants and components at the scheduled times and thus to the greatest possible extent an undisturbed operation of plants. Expert systems for process quality optimization and statistical process control as well as combustion optimization contribute to this to a significant extent.

In general, such expert systems support the operation of power plants in the following areas:

- Analyzing
- Detecting
- Optimizing

Smart solutions enable the operators of power plants to analyze complex systems and other installations to the most precise extent in order to locate and remedy possible controlling errors. By the means of such data analysis operators and engineers can detect deviations from the expected process data and locate potentials for improvement. Moreover, expert systems enable the optimization of processes within power plants.

For the activities of STEAG GmbH and STEAG Energy Services GmbH, a division of experts provides services and software solutions tailored for the demands of international and demanding projects. In the following three expert systems of STEAG Energy Services GmbH for process quality optimization and statistical process control as well as combustion optimization will be discussed in detail.
3. **SR::EPOS – Process Quality Optimization**

Within power plants, the condition of plant components (e.g. the heat transfer in a heat exchanger) as well as external boundary conditions (e.g. coal qualities, cooling water temperatures) are subject to constant change. In order to operate a power plant with an optimal efficiency, possible deviations from the optimal efficiency need to be detected, the cause will have to be identified and the mode of operation adjusted. Power plant technology and the process of converting energy are highly complex systems, so for optimal performance operators require tools which – founding on data available in the DCS or data historian – help to achieve the following goals:

- Increase transparency of the current state of the plant and the process
- Apply an economical evaluation to deviations to ensure that the priorities are defined correctly
- Spot errors, weak spots, malfunctions and areas for improvement
- Evaluate alternative modes of operation without negative impact on the plant

The expert system SR::EPOS of STEAG Energy Services GmbH is an exemplary tool for such tasks. SR::EPOS is a performance monitoring system that continuously analyzes and assesses the power plant process and thus reveals current economic losses, i.e. the potential for optimization.

Within the scope of online diagnostics, additional operating costs are shown to reflect deviations from the optimum conditions that are possible at that time. This allows to weigh the individual deviations and to take the required measures. SR::EPOS outputs the results in process images and trend diagrams (Fig. 1). Color changes draw the user's attention to significant deviations. The user can then jump from an initial overview to other more detailed levels. Using "what-if" calculations based on current operation measurements, changes in the mode of operation can be simulated continuously and automatically.

![Fig. 1: Result visualization in a process image and trend diagram](image-url)
3.1 Online Analysis with SR::EPOS

After commissioning SR::EPOS works online and evaluates the actual plant condition every five minutes. Efficiencies and other performance indicators for plant components like turbines, preheaters, condensers, cooling towers, pumps, fans etc. are being identified based on measured data and compared to reference conditions which should reflect the plants most optimal behavior as built. Deviations from optimal operation are displayed in process sheets for the operator. The reason for the deviation can be traced in a root-cause-analysis supported by offline simulation (see chapter 3.2). Daily performance reports are generated based on customized templates, triggered directly from the user interface. A constant evaluation of measurements via data reconciliation (VDI 2048) takes places, and data reconciliation reports give a listing of implausible measurements that can be specifically addressed in the next maintenance cycle. Systematic operational errors can be detected (also supported by offline analysis, see chapter 3.2) and therefore the overall efficiency is improved. From experience an improvement of 0.1 to 0.3 percentage points net efficiency is possible.

3.2 Offline Analysis with SR::EPOS

Offline analysis enables the user to simulate different operation strategies e.g. one vacuum pump vs. two, by passing preheaters for additional power output etc. In so called offline what-if calculations different scenarios like degradation/fouling of components, modernization measures, tracing of effects and economical evaluation of maintenance measures can be simulated. Various success cases from our customers proof that the physical model realistically reflects and therefore predicts the plant’s behavior in the aforementioned scenarios. Any idea for improvements can be simulated in the physical model by the efficiency engineers.

3.3 Knowledge Management

The process of implementation and usage of SR::EPOS is knowledge management as know-how and experience of the local operation and efficiency teams is transferred into the physical model. The model itself can further be maintained by a simulation specialist. At the same time the technical knowledge conserved in SR::EPOS can be integrated into business processes e.g. master data for electricity dispatch, aggregated fleet reporting for executives etc.

Documented findings during the various aforementioned phases – otherwise undetected for longer periods – are

- Weld cracking at the condenser
- Damaged sealing at the vacuum pumps
- Open ventilation valves
- Too low feed water temperature caused by flap of a HP-preheater
- Unintentional shut down of cooling tower zones
- Leaking valves in steam system
- Leakages / ingress of air in the ESP
- Detection of wrong measurement signals
3.4 Practical Example: Condenser

The expert system SR::EPOS enables operators to continuously monitor the condition of components. In this example a problem with the condenser could be detected and solved with the help of the process quality optimization tools SR::EPOS. Without the constant data analysis of SR::EPOS the operation could have continued in a less efficient way for a long time period without being detected.

The condenser problem was detected after a planned shutdown of the unit (Fig. 2). SR::EPOS detected a reduced condenser efficiency as well as a gap between the actual and the reference condenser pressure, that would not have been noticed without a supporting expert tool.

The cause of the described deviations was an open valve at the gland steam condenser leading to an increase of the condenser pressure. Within SR::EPOS the problem was visible immediately and could be fixed within the same day (Fig. 3).

The early problem detection with the help of SR::EPOS enabled the operator to fix a problem, that otherwise would have been unnoticed for months and would have caused additional costs. The monetary benefit due to monitoring and optimization with SR::EPOS in this case lies at approx. 150,000 €/month.

Fig. 2: Online analysis – Indication of Condenser Problems
4. SR::SPC – Statistical Process Control

Power plants and their components are subject to continuous changes in their operating behavior. Such changes have to be monitored continuously as otherwise they regularly lead to undetected deteriorations of the plant efficiency or to seemingly sudden failures of components with economic consequences. A continuous analysis of the operational data provided by the DCS of each power plant is required for monitoring any changes in the operating behavior at power plants. Due to the vast amount of data in the DCS, however, support by suitable IT systems that allow to derive the most important characteristics for the process and the main components is needed.

The expert system SR::SPC supports the power plant staff in fulfilling their tasks by continuously analyzing operational data and by reliably detecting changes and automatically reporting them by e-mail. SR::SPC has been developed for the qualitative description of power plant processes and components. It combines the classical approach of statistical analysis with reasonable additional tools such as neural networks, trend prediction, and advanced data filtering for maximum usefulness.

At first, SR::SPC calculates normalized quality characteristics in order to determine the current condition of a process or a main component. For this, the reference values belonging to the respective current mode of operation are calculated for important measured and characteristic values. By comparing actual and reference value, normalized quality characteristics, so-called KPIs (key performance indicators) are calculated, which are independent of the mode of operation of the plant and the ambient conditions. If an individual KPI deviates from a specified target value at a balancing time, this will be a first indication of an impairment. If this deviation recurs or increases at following points in time, the indication of an impairment will grow stronger. The chronological behavior of KPIs can be evaluated by means of methods of statistical process control (SPC). The SPC methodology has been developed to detect significant deviations of a process from a reference condition as early and reliably as possible.
One important element of statistical process control are so-called control charts. Control charts are diagrams that illustrate the chronological behavior of characteristic process parameters / KPIs. This way, deviations from the expected behavior that point out to faults can be detected earlier and more reliably than if only an isolated value were examined. KPI behaviors detected as critical are displayed to the user by SR::SPC in a web-capable overview (Fig. 4) by corresponding color changes in a traffic light system. In the overview, all monitored KPIs of a site can be conceived at a glance, so that the plant condition can be realized entirely with one brief look.

Fig. 4: SR::SPC Overview

By clicking on the KPIs, the stored control charts can be activated and analyzed in detail. Furthermore, previously defined e-mail recipients will be automatically informed about the current condition with a brief report (Fig. 5) in the case of conspicuous KPI behaviors.
The continuous monitoring of the KPI behaviors significantly contributes to detecting impending damages or problems automatically. “Overlooking” critical changes is largely ruled out as the responsible persons are automatically informed about a fault (process quality monitoring) or warned of an impending damage (condition monitoring) by e-mail.

**4.1 Practical Examples: Process Quality Monitoring and Condition Monitoring**

**4.1.1 Process Quality Monitoring, Example: Condenser**

Fig. 6 shows the successful application of SR::SPC using the example of a condenser. Smaller leakages and a fault of the vacuum system had led to ingresses of air and thus declines in the performance factor over a longer period of time. These ingresses/declines cannot be detected directly in the measured data of the condenser pressure (Fig. 6, left) as they occurred only during longer part-load operation and in addition were superimposed by other influences like e.g. cooling water temperature and district heating decoupling. They only become identifiable by converting the measured quantity into a KPI (Fig. 6, right). The SR::SPC online monitoring downstream detected and signaled the declines in the KPI without greater delay immediately at the beginning of the increased part-load phases with high district heating decoupling (see arrow).
4.1.2 Condition Monitoring, Example: Boiler Feed Pump

The following example (Fig. 7) shows the application of SR::SPC for assessing the condition of a boiler feed pump. In the described example the changes of the raw measured value are quite significant. However, a virtual limit value – e.g. a warning threshold in the DCS (dotted red line) – would have been transgressed unsubstantiatedly several times prior to the occurrence of the damage. Thus, no reliable notification could have been effected in a semi-automated way even with an optimal definition of limit values, and several false alarms would have been generated respectively – a monitoring system with such a rate of false alarms would not have been accepted by the operating staff for understandable reasons. By combining the tools for KPI determination and for statistical analysis of the KPI behavior, however, it was possible to achieve an unambiguous result of the analysis. In this case, the operator was informed about the changes online and thus promptly by the SR::SPC system. In the case of the boiler feed pump, the cause of the changes in the vibration characteristic was an incipient crack of the shaft.
5. Combustion Optimization

The combustion in power plants is a complex process with a number of known parameters, but also with several unknown influencing variables. To date, mainly procedural know-how and a certain amount of “intuition” are required for controlling and optimizing the combustion. Based on existing data plus wide experiences it is necessary to adapt the combustion to the specific properties of a plant and a fuel. Here the essential approach for a combustion optimization consists in adapting the distribution of air to the coal qualities and to the particular distribution of pulverized coal as well as the properties of the boiler.

Manually, such an optimization will usually be feasible for a limited load range as well as a limited range of fuels. All influencing variables that may lead to fluctuations, like e.g. frequently changing loads and/or different coal qualities, thus finally result in a combustion setting that is not optimal. In the context of the central topics of economic efficiency and flexibility, a continuously optimized combustion can improve the efficiency of a power plant and thus decrease costs. In addition, it enables the use of fuel qualities that previously were not intended for the operation of a plant. Last but not least it allows faster load ramps within certain limits, prevents emission peaks, and also helps to decrease minimum loads by stabilizing the combustion in a way yet to be described.

To be able to achieve this, the existing expert knowledge has to be supported with new technologies. A crucial basis for this is provided by software systems for the combustion optimization; modules for the modeling, optimization, and DCS integration represent fundamental elements of such solutions (Fig. 8).

![Fig. 8: Elements of a combustion optimization in the closed control loop](image_url)

Whilst there are different approaches to conduct combustion optimization, in this paper the variant of a non-sensor-based solution will be discussed:
5.1  **Non-sensor based combustion optimization**

First of all, for setting up a combustion optimization it is important to know the relation of the required target variables (e.g. improved efficiency, higher flame stability, etc.) to the manipulated variables that can be influenced via the DCS. As the coherences are complex and not known a priori, they have to be derived from the available data. Prerequisite for this is that the data can be read from the DCS and data can be written into it, because a combustion optimization is always also a closed loop solution that intervenes in a closed control loop e.g. in order to make changes to set point values. The combustion optimization by Advanced Process Control therefore always requires a bidirectional communication with the DCS. Such a coupling and an access to the DCS network respectively is either possible via an OPC (OLE for Process Control) or a bus system like e.g. Modbus/TCP.

In a second step, software for generating data-based models is to be implemented. These models can be created based on existing in-service measurements (e.g. for air quantities, flap positions, and rotation speeds of classifiers and metering hoppers of the individual mills, emission values, etc.), which are recorded in a time series archive during operation. Mostly it is necessary to supplement these data by additional tests in the plant, further refining the models. The result is a statistical description on how processes behave in certain operating situations. For the process modeling either neural networks, probability-based statistical models, or a combination of physical and data-based models (gray box models) can be used.

5.2  **Automated optimization of specific processes**

When the process model has been created, another software module determines the optimal condition in reference to a predefined target variable. By means of the generated model, this software basically answers the questions that arise regarding the goals in individual processes. These may be questions like: what is the optimal process control for the current coal type or the current load? Which combination of manipulated variables is required for reducing emissions or increasing the efficiency?

To put it simply, the first software module has the task to create models that can be adapted to certain target variables via free parameters, whereas the second software module evaluates these models in order to identify the manipulated variables by means of which the process can be improved, depending on a specific question and goal respectively.

The instructions required for such manipulated variables are transmitted to the DCS via the bidirectional communication interface described above. This is an automated process that autonomously intervenes in the DCS in order to make the necessary changes to the respective manipulated variables.

5.3  **Automatic tests and feature selection**

The software components described so far are the basis of the combustion optimization in the closed control loop. However, further modules are essential for a lasting and efficient implementation. They ensure that the optimization system can continuously adapt to new process conditions; in addition, they make sure that a maximum of information is available to the models.

As mentioned above, a process model based on historical data (in-service measurements) as well as additional tests in the plant can be created by means of software. When these tests are conducted manually, they are very time-consuming. It is far easier and more efficient to carry out such tests automatically during the regular operation of the power plant. One of the advantages is that after implementing a respective system for combustion optimization,
automated tests can be conducted again and again and at any time, without restricting the power plant operation.

Based on such automatic tests, the system is able to identify possible operational changes of the plant and to autonomously as well as continuously adapt to these changed conditions. The causes of such changes may be e.g. the wear of certain plant components but also a new coal type, to name just a few examples. The system basically watches the quality of the process models, thereby detects if there are deviations, and then autonomously decides whether the models have to be adjusted or not. If adjustments are necessary, these will be effected automatically and continuously during the operation of the power plant.

Another special attribute is the automatic feature selection. It ensures that a minimal number of channels with a maximum of relevant, objective information is available for the modeling. As explained above, a vital intention of the combustion optimization consists in modifying certain target variables. Precisely determining the manipulated variables that influence such target variables sufficiently strongly and reproducibly is prerequisite for this. The feature selection supports the modeling in a perfect way as it can also identify such manipulated variables automatically. For this, advanced algorithms from robotics/neuro-informatics are applied that filter out those of the existing in-service measurements and, if applicable, sensor data which contain the most information on the target variables to be influenced. With such modules, a combustion optimization is supplemented by components that lastingly objectify the activities for an expedient combustion optimization.

Against this backdrop, the special attributes of such systems can be described with the qualities "self-learning", "adaptive", "permanent", and "flexible". Self-learning as mathematical / statistical models are not based on expert knowledge but automatically learn from the currently existing process data. The term "adaptive" is used because the process models autonomously gain additional valuable "experiences" to expand the knowledge on new process situations. Moreover, the models permanently optimize themselves independently, even when the process results are satisfying but yet potentials for optimization arise. Besides, desired optimization goals can be changed easily and flexibly without the need for re-programming or re-parameterizing the software.

5.4 Required interventions in control loops

The systems for a combustion optimization introduced so far consist of four software modules, among them basic modules for the modeling and for optimizing a corresponding action plan, as well as two crucial additional modules for automatic tests and for the automated selection of the most important manipulated variables. Not only is a bidirectional interface to the DCS prerequisite for implementing these solutions. For integrating the systems into the control and closed-loop control of the plant it is also necessary to modify the existing control loops of the power plant in such a way that they allow interventions in processes. In most of the cases, such a structure does not exist beforehand. Therefore the DCS is to be supplemented by a corresponding set point control; here, however, the necessary offsets of the manipulated variables can be entered into the respective control loops with little effort.

Beyond the described basis, now the chance arises to receive a crucial gain in information by using sensors in order to tap further potentials for the combustion optimization.

5.5 Practical Examples for Combustion Optimization

These solutions have been successfully implemented in a number of pulverized coal fired power plants. The Jharsuguda unit 1 is a typical example of a non-sensor based closed loop combustion optimization. It is a 600 MW unit with a natural circulation boiler with 24 low-NOx burners (tangentially fired) in 6 levels with ball mills utilizing coals from different sources (Fig. 9).
After commissioning of the DCS connection, the optimization solution is in operation since October 2013. Off-site and on-site fine tuning took not more than 4 months, so that the project could be successfully completed by February, 2014. The operator is free to activate/deactivate the system at any time. It generates corrective biases, but the traditional mode of plant operation remains available and unchanged. It operates within predefined ranges for all biases and bumpless activation and deactivation is ensured. The functioning of the DCS-connection is monitored automatically.

By means of the implementation of a closed loop combustion boiler operation was stabilized and efficiency increased

- by reduction of flue gas temperature left-right imbalance to avoid metal temperature hot spots
- by reduction of fluctuations in RH-temperature and spray
- by reduction of average RH-spray and increase of average RH temperature for different mill combinations and for different load demands (Fig. 10).
Fig. 10: Achieved improvements in Jharsuguda

The metal temperature excursion has been reduced by more than 50% and the unit-heat rate has been improved by 5 kcal/kWh by higher average steam temperatures and reduced RHspray.

Another example is the implementation in the Tanjung Bin Power Station, unit 30. It is a 748MW unit with a natural circulation boiler, 30 low NOx burners in 3 levels with front and back firing, see Fig. 11

<table>
<thead>
<tr>
<th></th>
<th>From normal operation</th>
<th>To Pit Navigator</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Av. duration of RH-Metal Temperature excursion</td>
<td>13min/d</td>
<td>5.9min/d</td>
<td>&gt;50%</td>
</tr>
<tr>
<td>Av. RH-Steam Temperature</td>
<td>532.2°C</td>
<td>535.2°C</td>
<td>3K</td>
</tr>
<tr>
<td>Av. RH-Spray</td>
<td>49.8t/h</td>
<td>43.9t/h</td>
<td>6t/h</td>
</tr>
<tr>
<td>Av. SH-Steam Temperature</td>
<td>538.4°C</td>
<td>539.2°C</td>
<td>0.8K</td>
</tr>
</tbody>
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Fig. 11: Boiler, burner and air arrangement

By means of the closed loop combustion optimization the boiler efficiency could be increased by reduction of average excess O₂ and by reduction of average flue gas temperature for different mill combinations, load demands and coal blends. The global and local CO levels were kept below certain limits to prevent wall corrosion. Fig. 12 shows the improvements in exit O₂ and exit gas temperature for different coal blends.
Fig. 12: Improvements in exit O₂ and exit gas temperature for different coal blends

On average the exit O₂ was reduced by 0.6% to 0.8% and the flue gas temperature at economizer outlet by up to 4 K. This results in coal savings of about 15.600 t/a and in a reduction of auxiliary power consumption of the IDF/FDF fans of about 2700 MWh/a.

6. Expert Systems - Smart Solutions for Power Plants: Conclusion and Outlook

Modern DCS technology has brought plenty of advantages for power plant owners and operators. Tough market conditions, high demands with respect to operational safety, and declining numbers of operating personnel, to mention only a few influences, have put high requirements on the staff. Smart software systems can support the staff and ensure that the tremendous available possibilities can be used to prevent damages and efficiency leaks – promptly and even under hectic and stressful everyday working conditions.

Smart solutions for power plants can support operators and engineers in different areas. Monitoring systems like SR::EPOS enable continuous gathering and analyzing of data and thus can help to detect various problems very fast in order to avoid a reduction of efficiency or damages.

Also the use of statistical methods lends itself for obtaining reliable indications of impending faults by continuously evaluating existing performance values as early as possible. The expert system SR::SPC offers the opportunity to monitor different departments and production lines as well as several third-party systems in only one clearly laid out view. Without such a compiled view, often several different systems (used for the same unit but different tasks, e.g. emissions, water treatment, water-steam cycle etc.), which are not interconnected, have to be used in parallel, and it takes a lot of manual effort e.g. to compile reports for managerial or official purposes.

Moreover, the optimization of combustion within power plants enables operators and engineers to increase the plant’s efficiency. The software based combustion optimization tool PiT Navigator enables continuous closed loop operation and with that the increase of efficiency. It can be integrated into DCS via limited biases to manipulated variables while the DCS functionality remains available and unchanged. The approach of STEAG Powitec’s PiT
Navigator is to explore the process automatically to record informative data, learn the process model from existing data and also to enable the calculation and closed-loop application of optimal biases.

In order to manage and master modern requirements of power plants, it is crucial to make use of all technical reasonable options as well as prevent unnecessary trouble, failures and downtimes. Speaking from experience the saying "A small leak can sink a great ship" applies to most power plants.

Therefore, smart solutions for power plants enable plant operators to take another step towards optimizing process efficiencies and thus saving emissions and increasing power generation efficiency.