

Efficiency up, emissions down

Achieving higher power plant performance with advanced process control
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Coal-fired power plants have come a long way in the last decades to become generators of electrical energy with high efficiency and sharply reduced emissions. Big steps have been taken particularly with improved boilers, steam turbines and improved cycles.

Only recently, however, were advanced process control technologies – well established in other industries – made available for power plants. ABB's multi-variable model predictive control (MPC) has now demonstrated its superior performance and realized significant energy savings and emissions reductions. The plants utilizing ABB's technology have realized NO_x reductions of eight to 40 percent, while generating tens of GWh per year of additional electrical energy with the same fuel consumption.



Process Innovations

Multi-variable model predictive control (MPC) is a technology with superior performance over traditional single-input/single-output control strategies **Factbox**. Originally developed for petroleum refineries, MPC has become common in process industries over its 30 years in applied practice. Only recently, however, has MPC found its way to power plant control and optimization.

This slower progress in the power sector can be partially explained by higher performance requirements. The dynamic behavior of power plant components is usually much faster than that found in petrochemical processes, and it requires computing power that until recently was either not available or not cost-effective. In times of low primary energy cost and less strict requirements on environmental issues, the economic advantage was also not as substantial.

The increasing performance of computers has now made it possible to apply MPC to demanding large power plant applications. For industrial power plants, smaller in size, MPC solutions have already been implemented, focusing on coordinated control and optimization of multiple boilers, fuels, turbines, steam headers and power flows to and from the grid. The range of benefits in industrial power plants, such as improved plant stability, higher availability and lower overall energy costs, have paved the way for a wider application in large power plants [1].

The most common application of MPC for large utility power plants today is combustion optimization, dealing with optimum distribution of fuel and air in the boiler to reduce emissions (particularly NO_x), while improving combustion efficiency [2].

More recently, MPC-based solutions have been deployed in other areas of the plant, such as main and reheat temperature control and boiler-turbine coordination. ABB's OPTIMAX® portfolio addresses these solutions and contains a variety of technologies, such as the Predict & Control software, which is among the most advanced MPC solutions applied in both industrial and utility power plants.

Performance improvement with MPC
The primary objective of advanced process control is to reduce process variations. For power plants, this means improved process stability and reliability, and reduced thermal cycle stress on the high pressure parts.

With reduced variance, the power generation process can also be oper-

ated closer to the given plant's optimum. In many cases, this optimum is defined by constraints. By minimizing variations, the process can be pushed closer to its limit without violating the constraint **1**.

In a utility power plant, a large number of possible process constraints exist. Some of these are listed in **2**. The benefits from operating closer to the limits include improved heat rate, higher generation capacity and lower emissions.

Multi-variable model predictive control also facilitates faster ramp rates, while keeping the plant within the acceptable operating envelope in the ramp-up. This can be very beneficial for units in cycling operation, and in boiler runback situations.

ABB'S Predict & Control

Historically available MPC packages, often used to implement advanced control solutions in process industries, show a number of serious deficiencies [3].

- There are limitations in the choice of control models. The commonly available impulse and step response models can only be applied for inherently stable processes, and they handle integrating processes poorly
- The controllers work poorly in the presence of significant measurement noise or unmeasured disturbances
- Model identification relies on open loop step testing, and only single-input/single-output (SISO) models can be identified

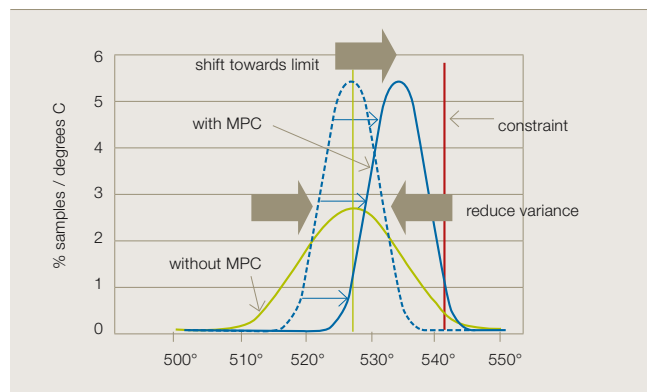
Without a more comprehensive commercial software solution, ABB began work on a full-fledged MPC-based system. The new product, Optimize^{IT} Predict & Control (P&C), could overcome the shortcomings of the previous solutions. P&C is based on new technology that replaces the typical collection of SISO step response models with a true multiple-in-

Factbox Multi-variable model predictive control (MPC)

MPC is a common name for control technology using dynamic process models representing the relationship between independent variables (model inputs) and dependent variables (model outputs). The inputs include manipulated variables (MV) and disturbance feed-forward variables (FF). The model outputs are called controlled variables (CV). The models predict future outputs based on 1) past values of manipulated variables, 2) calculated future values of manipulated variables and 3) past values of the feed-forward variables.

A multi-variable MPC algorithm uses inherent knowledge of the process dynamic behavior. All the interactions between the process quantities are considered in the simultaneous solution of many equations. This is different from traditional control (eg, PID control), where each controller has one input and one output. With the many constraints and complex interactions involved in power plant control, multi-variable MPC is well suited to provide advanced control and optimization in the power industry.

1 Reduced variance of steam temperature allows an operation closer to the limit



put/multiple-output (MIMO) state space model¹⁾ [4].

The new ABB algorithm identifies accurate state space models from plant test data. The ability to identify MIMO models from a single set of closed-loop tests reduces the required testing time and greatly simplifies the modeling task.

The Kalman filter is a mathematical technique that utilizes all available information to develop the best estimate of the process state and the disturbances affecting it.

The state space modeling approach permits P&C to use a Kalman filter for state estimation as part of the feedback control algorithm. The Kalman filter is a mathematical technique originally developed for trajectory estimation of space craft. It utilizes all available information to develop the best estimate of the process state and the disturbances affecting it. Besides the controlled variables, additional process measurements can be included in the model, providing the Kalman filter with more information and further improving state and disturbance estimation.

2 Examples of process constraints for utility power plants

- Maximum live steam temperature
- Maximum live steam pressure
- Maximum steam flow
- Maximum reheat temperature
- Minimum flue gas O₂ content
- Maximum opacity of flue gas
- Maximum NO_x emissions
- Maximum generator power
- Minimum condenser vacuum
- Maximum fan capacities (amps or dampers)
- Windbox pressure differential dampers

Footnote

¹⁾ A state space model describes a physical system with a number of differential equations.

The basic principle of the P&C controller is shown in **3**. At each pre-defined time interval, the controller reads actual process variable values and uses the process inputs (u) and outputs (y) to estimate the current process state (\hat{X}), input disturbances (w) and output disturbances (h). This approach is different from standard MPC packages that can estimate the output disturbances only (h). This leads to far better estimates of the state (\hat{X}) and better control of y.

Optimum MPC design

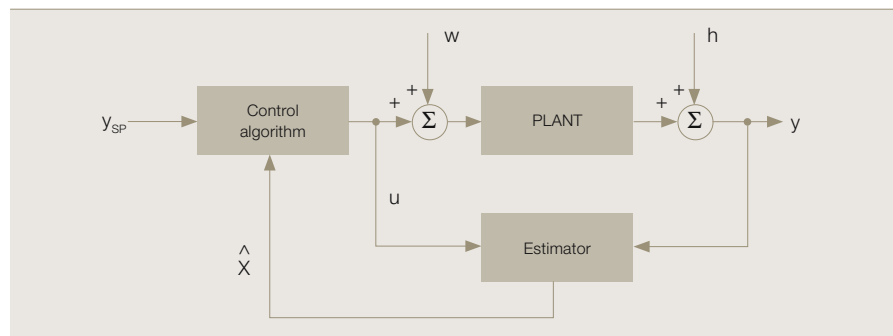
In a power plant, a large number of inputs (manipulated variables that can be set, and feed-forward variables generated by disturbances) and outputs (controlled, constraint and addi-

tional state-estimation process variables) exist that can be used for the control model. The selection of the model scope with the required inputs and outputs depends on the project objectives, plant configuration, and the specific local economic factors.

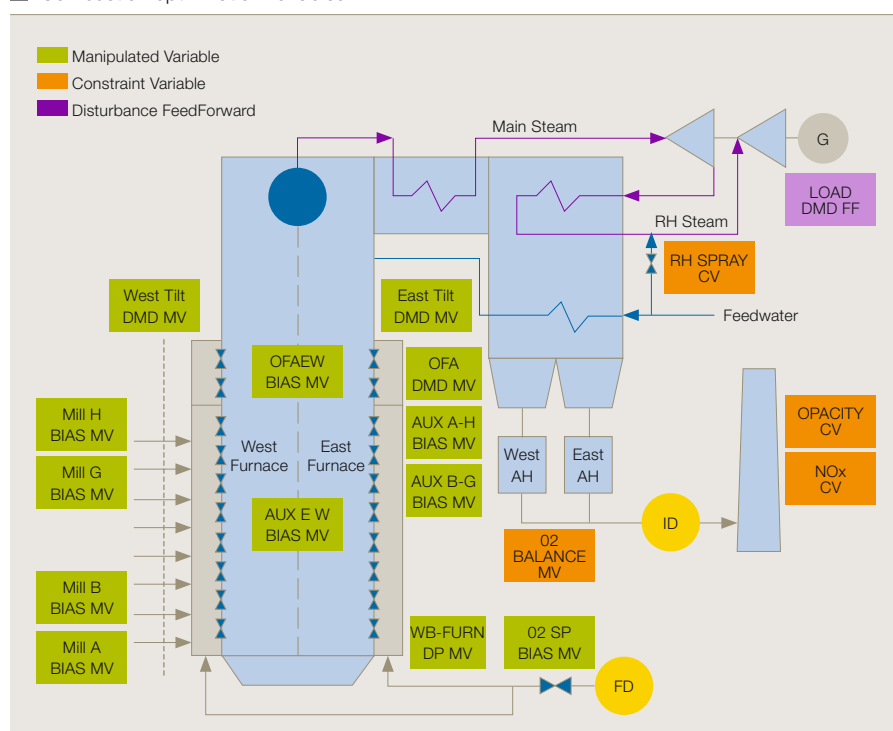
The MPC inputs and outputs for a typical combustion optimization task are illustrated in **4**. The manipulated (MV), feed-forward (FF), and constraint (CV) variables for this divided furnace boiler are indicated.

The relationships between these parameters are shown in **5**. The different rows of the matrix represent model inputs; the columns define outputs. The matrix elements with a check-

3 Basic principle of ABB's Predict & Control controller



4 Combustion optimization variables



Process Innovations

mark indicate physical relationships included in the overall model.

The above scope represents traditional combustion optimization systems, where the attemperator²⁾ spray flows are included as process constraints. The purpose is to keep the base controls for main and reheat temperatures

within a favorable control range, and to minimize reheat spray flow.

Once the model scope has been defined, the engineering tools within P&C can be used to create and modify the structure of the multivariable controller. A user-friendly application browser is available to define the

manipulated, controlled (or constraint) and the feed-forward variables. Properties associated with these variables are also defined using the configuration tool.

Predict & Control is typically implemented at the supervisory level to manipulate set points of multiple base control loops implemented in the digital control system (DCS). Examples of such set points include fuel flow, attemperator flow and oxygen set points. For best results, it is important to have the base loops – including sensors, actuators and other field instrumentation – properly tuned and in good working order. ABB's Loop Performance Manager (LPM) is part of the same Advanced Process Control Suite as Predict & Control, and the loop tuning and auditing capabilities of LPM improve the base loops prior to the MPC commissioning.

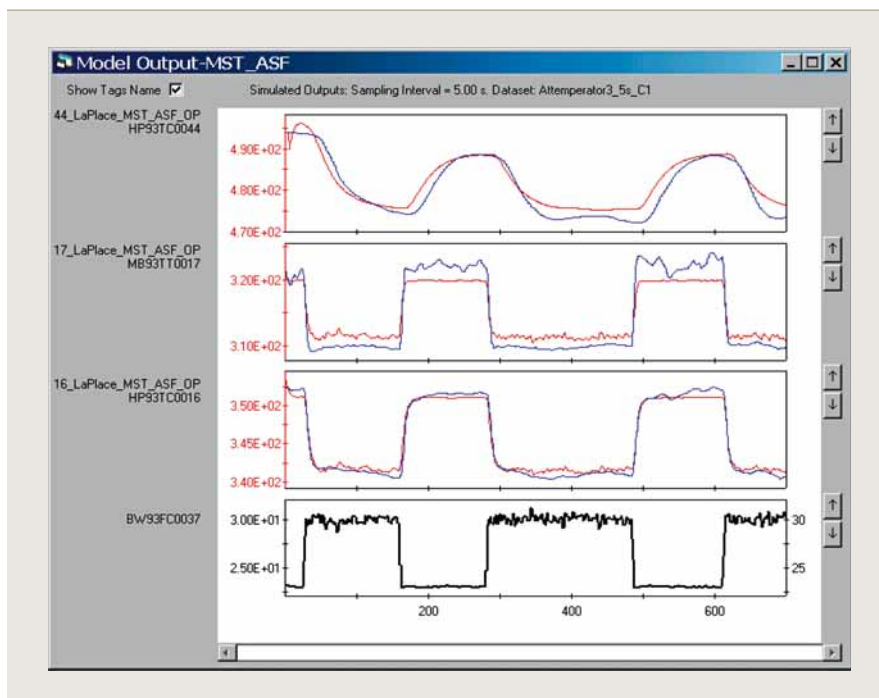
The engineering tool has a powerful data processing capability for importing, trending and filtering the collected process data, including automatic outlier identification and removal. The computational core of the modeling tools is the parametric identification tool that is used to build state space models. The state-of-the-art algorithm combines ease of use with the ability to utilize both open- and closed-loop test data in the model identification. Trend displays are provided to illustrate the fit of the identified models to the actual measurement. A boiler main steam temperature control example is shown in [6](#), comparing the actual temperatures (red) to the values predicted from the attemperator spray moves (blue).

The final step in MPC design is the tuning of the controller to the specific plant. With the help of weight parameters for the various feedback loops, the MPC is tuned to produce the desired dynamic response of the plant. The tuning includes setting weights on control errors and drifts of the different variables. A large weight is set when a small control error or drift is allowed, and vice versa. Priorities are also assigned to the various constraints. In case of conflicting constraints, the one with higher priority is satisfied first. If adequate degrees of

5 Combustion optimization control matrix of input and output relationships

| MV | CV ==> | NO _y | STACK OPACITY | O ₂ IN BALANCE | REHEAT A SPRAY DMD | REHEAT B SPRAY DMD |
|--------------|-----------------------------|-----------------|---------------|---------------------------|--------------------|--------------------|
| | | ppm | % | % (O ₂) | % | % |
| O2 SP BIAS | O2 Setpoint Bias | - | - | | | |
| WB FURN BIAS | Windbox DP Setpoint Bias | - | | | | |
| AA FF BIAS | Aux Air East-West Bias | | | - | | |
| AA AH BIAS | Aux Air Elevation A-H Bias | - | - | | | |
| AA BG BIAS | Aux Air Elevation B-G Bias | - | | | | |
| MILL H BIAS | Mill Feeder H Bias | - | | | | |
| MILL G BIAS | Mill Feeder G Bias | - | | | | |
| MILL B BIAS | Mill Feeder B Bias | - | | | | |
| MILL A BIAS | Mill Feeder A Bias | - | | | | |
| TILT DMD E | Burner Tilt East Demand | - | - | | - | |
| TILT DMD W | Burner Tilt West Demand | - | - | | | - |
| OFA DMD | Overfire Air Demand | - | - | | | |
| OFA FF BIAS | Overfire Air East-West Bias | | | - | | |
| FF | | | | | | |
| GENERATOR MW | Unit Load Demand | - | | | | |

6 Comparison of model predicted and measured temperatures in a power plant



freedom and control capacity exist, additional constraints are resolved in rank order.

The whole plant at a glance

Operators of power plants need a fast and complete overview of the plant status with all details available on request. There are two ways to monitor and access the P&C-based advanced control system. The controller may use OPC to link all operating parameters to a DCS console, facilitating true single-window operation of the plant, or the operator can use the P&C Operator Interface client.

A typical optimization overview is shown in 7. It can be used to monitor the status of the advanced control and optimization, and to enable or disable optimization for any given component.

A track record of impressive savings with P&C

Advanced model predictive control systems have established a track record for improving plant operations. Some of the improvements include the following:

- Typical NO_x reductions of 8 percent at base load, and up to 40 percent at swing load
- Heat rate improvements of
 - 0.25 – 1.5 percent at base load
 - 1.5 – 2.5 percent at swing load
- Reduction of unburned carbon in ash by 1 – 5 percent
- Reduced CO₂ generation per MWh generated
- Maintenance of CO at desired levels
- Improved availability
- Accelerated ramp rates

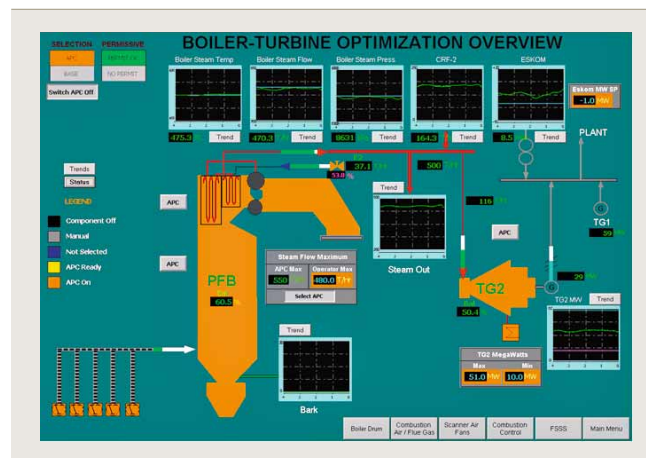
Footnote

²⁾ The attemperator is a device that adjusts the temperature of the spray flow to the required value.

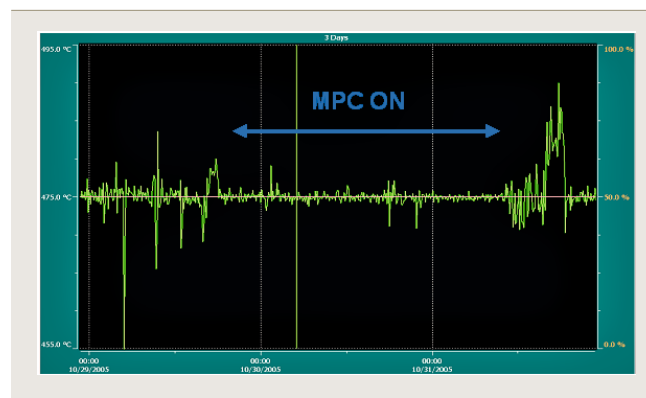
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7 Single-window overview of the status of a boiler-turbine optimization



8 Improving heat rate through better main steam temperature control



A significant improvement of the boiler performance can be achieved with an operation at the highest possible main steam temperature. 8 illustrates how temperature variations can be reduced by means of multi-variable MPC, the precondition for a safe operation at the maximum temperature. In this case, the improved control of a pulverized coal boiler reduced the standard deviation of the main steam temperature by 80 percent, allowing a set point increase of 10°C. While 10°C may sound small, the

resulting heat rate improvement was 1.2 percent, which adds up to approximately 10,000 MWh per year of additional power generated from the same fuel input.

Heat rate improvements can also be achieved by adjusting reheat spray flows as constraint variables. Because of the reduced variations in the flow rate through MPC control, they can be reduced and operated closer to the limit. By cutting the spray flow rates to one-half of the original, the corresponding heat rate improvement in another application was 0.36 percent, providing approximately 25,000 MWh of additional power per year with the same fuel consumption. At the same time, NO_x emissions fell by 10 percent.

As the examples show, MPC-based control systems have a significant impact on power plant operations, energy efficiency and emissions. MPC is a powerful instrument to meet a fast growing need in the utility business – that is, simultaneously achieving both economic and environmental benefits.

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