Optimize^{IT}

Model predictive control for boiler start-up (BoilerMax)

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The marriage of model-based closed-loop control and information technology offers a new level of efficiency and productivity to many industrial areas. It is especially true in steam power generation, where automation is indispensable for the operation of the large boilers that generate the steam used to drive the turbines. Here, such a union provides the ideal basis for minimizing thermal stress – the cause of shortened lifetime – as well as energy consumption during the fast boiler start-ups.

A non-linear, model-based predictive controller (NMPC) developed by ABB meets these requirements while taking into account a whole series of constraints. It is the first of its kind to be successfully used in a power plant rated at around 700 MW_{el}. Experience to date shows that, thanks to its broad functionality, the NMPC solution could be easily adapted for similar applications in other industrial sectors.

Modern IT-based automation systems are fast becoming the systems of choice for developing model-based closed-loop control strategies for industry. With only conventional technology available, a huge amount of effort was needed in the past to fulfill the wide range of requirements that these new strategies are able to satisfy.

Model-based closed-loop control strategies are being recognized as powerful solutions to specific automation problems. At the same time, field experience is confirming that the new quality of automation they allow translates into added value for industry.

Controlled steam generator start-up

Optimize^{IT} Model Predictive Boiler Start-up Control (BoilerMax) was developed by ABB to enable all of the advantages of uniting model-based closed-loop control and IT to be applied to steam generators in large power plants. The new system is based on dynamic optimization and a derived closed-loop control technology – the non-linear model-based predictive controller (NMPC). Its dynamic mathematical model, in this case of a steam generator, enables BoilerMax to spot trends as they develop and be pro-active. Armed with this feature the NMPC can satisfy a whole host of requirements that are beyond the reach of conventional closed-loop controllers. In the case looked at here, that of optimizing the start-up of a steam generator, this extended capability includes taking into consideration the maximum thermal stress allowed in critical thick-walled components.

The described control system is in use in a large power plant, and represents the first successful application of an NMPC for starting up steam generators of this size. The wide-ranging functionality built into this solution also makes it easily adaptable to other areas where similar requirements exist.

The problem with steam generators

At the simplest level, the operation of a steam generator can be likened to that of a coffee maker: water is heated from a low to a high temperature. But whereas most coffee makers use an electrical current to generate this heat, many large power plants produce it by burning coal, gas or oil.

The furnace in which the coal is burned can be imagined as a gigantic hall, 30 by 25 meters in area and as much as 130 meters high. Fixed to its walls are thousands of steel tubes, each one as thick as a man's arm and together weighing thousands of tons. The temperature inside this chamber can lie anywhere between 600 °C and 1100 °C. Steam is produced at a rate of more than 2000 tons per hour. Its temperature is about 520 °C and it is at a pressure of approximately 150 bar.

The tubes carrying the steam from the furnace are brought together in manifolds, and it is these in particular that can cause problems. They are exposed to extremely high thermal stress during start-up that leads, eventually, to material fatigue. This makes them a key cost factor in plant operation. In fact, replacing the manifold – usually referred to as a superheater header – can easily cost as much as a standard detached house. Obviously, being able to control and optimize the start-up, and so minimize this stress, has the potential to be a major cost-saver.

Steam generation in large power plants

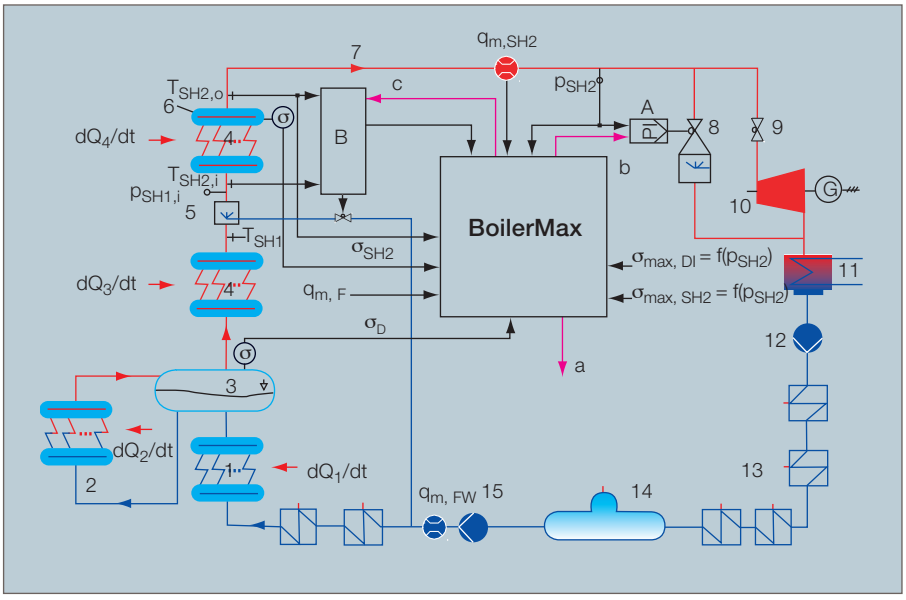
To appreciate the benefits of BoilerMax it is first necessary to understand how a large steam generator works 1. (In this diagram the blue and red lines represent the water/steam circuit, the black inputs supply BoilerMax with information about the actual status of the steam generator, and the magenta outputs represent the optimized control variables, ie the setpoints for the secondary controllers).

> BoilerMax represents the first successful application of an NMPC for starting up steam generators in large power plants.

The job of the economizer in this circuit is to preheat the feedwater. The evaporator that follows it produces so-called saturated (or 'wet') steam, which afterwards has to be superheated. Although the figure shows just two superheaters, an actual power plant has a large number of these (eg, 20) arranged in bundles. Some of them have a so-called attemporator connected upstream for the purpose of temperature control. At the inlets and outlets of these superheaters are headers – critical components because of the high thermal stress they are exposed to. These are where the tubes exiting the combustion chamber come together and where the steam from the smaller tubes is collected 2.

The steam flowing from the final superheater stages is collected and led through a so-called live-steam pipe to the high-pressure bypass station (HPB), which is located near the high-pressure turbine. As long as the steam has not reached the operational values (ie, for the duration of the start-up)

1 Basic diagram of a steam generator circuit with superimposed BoilerMax system



1	Economizer
2	Evaporator
3	Drum
4	Superheater
5	Attemporator
6	Header
7	Live-steam pipe
8	HP bypass
9	HP turbine valve
10	Turbine
11	Condenser
12	Condensate pump
13	LP feedheater
14	Feedwater tank
15	Feedwater pump
A	Live-steam pressure control
B	Superheater temp. control
a	Fuel mass-flow setpoint
b	Superheater temp. setpoint
c	Live-steam pressure setpoint

2 The superheater headers, with their 6.4 cm thick walls, are especially sensitive to thermal stress.

it is led via the HPB into the condenser. The condensed steam then flows back through several heaters and the feedwater tank to the economizer, whereby the water-steam circuit is closed. During normal operation, ie after start-up, the steam flows through the turbine valve to the turbine. While this is happening, the HPB remains closed.

The steam generator's behavior can be described mathematically, in the form of a dynamic model, by means of thermodynamic equations. Detailed descriptions of this can be found in the literature, eg [1]. The difficulty here lies in obtaining models of the steam generator which are sufficiently precise and which allow the equations to be solved in finite time. The time factor is especially important for on-line automation engineering applications.

The start-up process

Steam generators experience three main types of start-up:

- Cold start: The heating space has been allowed to cool down completely, eg for maintenance work.
- Warm start: This follows a disconnection of the power plant from the grid lasting about 30 to 50 hours.
- Hot start: The furnace is restarted within 4 to 30 hours after a shutdown.

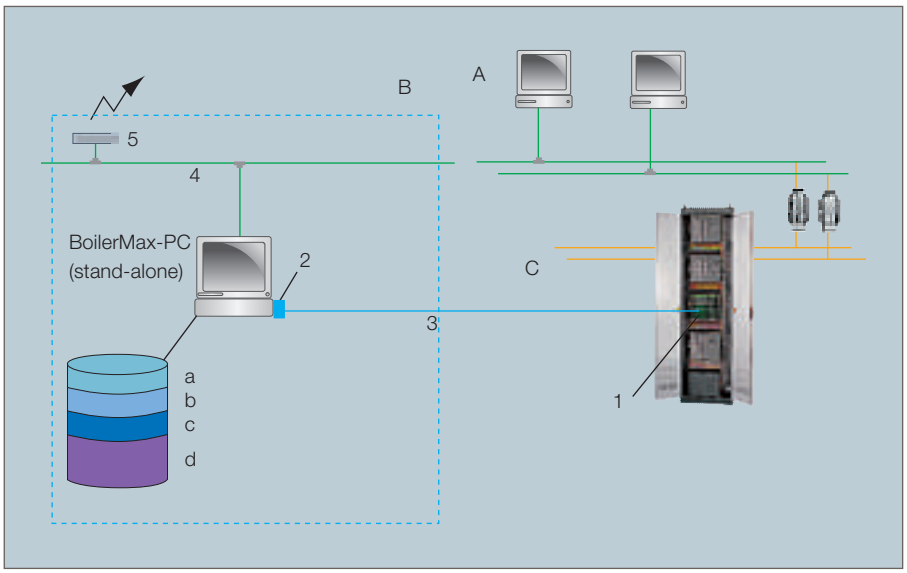
In all three cases the fire in the combustion chamber is out for the duration of the shutdown.

In the past, it was usual for large power plants to be base load operated for most of the time and for them to be connected to the grid all through the year. Market deregulation and the energy trade market have now changed all this. The resulting shift toward medium load operation has meant that plants are started up and shut down more frequently, primarily at weekends. As a consequence, start-up losses are drawing far more attention than before.

Defining the problem

What is it, then, that makes the start-up of large steam generators in particular such a problem? Generally speaking, there are three problem areas:

3 Example of how BoilerMax can be embedded in an existing instrumentation and control system



1	PROFIBUS-DP master unit
2	PROFIBUS-DP slave PC plug-in card
3	PROFIBUS-DP connecting cable
4	PC application network
5	Modem
A	Control room
B	Control side-room
C	Electronics room
a	OPC server (PROFIBUS-DP)
b	OPC client
c	Real-time environment
d	BoilerMax application

- Temperature gradients occur in the steel tubes due to the changes in temperature during firing. These cause thermal stress in the tubes, and particularly in the headers [2]. If the thermal stress is too high it can shorten the headers' lifetime, which can have a substantial knock-on effect for a power plant's profitability.
- The steam generator is, for theoretical purposes, a multi-variable system. The two control variables (the fuel/air flow and HPB position), for example, influence the output (the steam), but also affect the two controlled variables (the steam pressure and temperature). The relationships between the control signals, the system's output and the values for the steam pressure and temperature are strongly non-linear. The reason for this is the dependency of the steam density and energy content on the steam pressure and temperature. An additional problem is the non-linear relationship between the steam pressure and mass flow.
- A start-up is, from the utility's standpoint, nothing but a cost factor, since no electrical power is produced. The cost is particularly high since the fuel used at this stage is usually oil or gas. Often, too, an external supply of steam is needed. Revenues, on the other hand, cannot be generated until power is fed into the grid.

Where dynamic optimization comes in

Two conventional strategies are generally used. One foresees operation at a safe distance to the thermal stress limits, while the other accepts limit violations. To be on the safe side, the thermal stress limits are chosen conservatively.

More powerful strategies can be implemented when a dynamic mathematical model of the steam generator is used. However, this presupposes that the expected thermal stresses can be reproduced with sufficient accuracy.

This is where dynamic optimization comes in. By allowing optimal trajectories to be calculated for the control variables 'fuel/air flow' and 'HPB-valve position', it ensures that the steam passes from its initial state to the desired final state – the operating point. Moreover, it allows existing constraints to be taken into consideration, a feature that most other approaches lack.

Formulating the problem

For the described application, the optimization problem is formulated as an optimal control problem as follows:

$$J = \int_{t=0}^{t_f} \frac{\left[T_{LS}(t) - T_{set}\right]^2}{w_T^2} + \frac{\left[p_{LS}(t) - p_{set}\right]^2}{w_p^2} + \frac{\left[q_{mLS}(t) - q_{m,set}\right]^2}{w_{q_m}^2}\, dt \rightarrow \min_{q_{mF}(t), Y_{HPB}(t)}$$

such that

$$\dot{x}(t) = f\left[x(t), q_{mF}(t), Y_{HPB}(t)\right], \quad x(0) = \bar{x} \qquad (1)$$

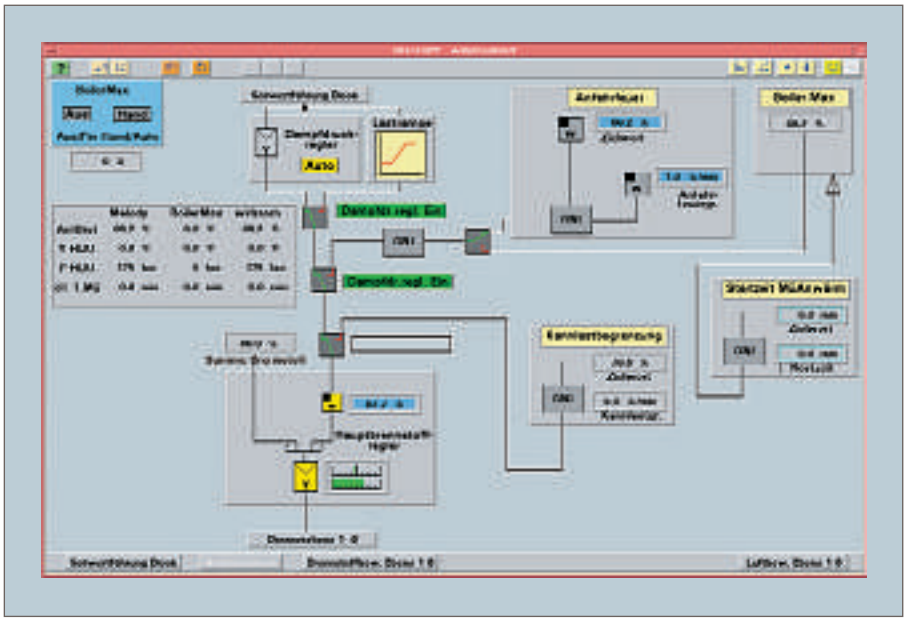
$$q_{mF,\min} \le q_{mF} \le q_{mF,\max}, \quad \dot{q}_{mF,\min} \le \dot{q}_{mF} \le \dot{q}_{mF,\max} \qquad (2)$$

$$0 \le Y_{HPB}(t) \le 100\% \qquad (3)$$

$$-\Delta T \le \Delta T_x(t) \le \Delta T \qquad (4)$$

As is seen, objective functional J, which is to be minimized, contains the differences between the target setpoints (index *set*) and the live-steam values (index *LS*) for the temperature T, pressure p and mass flow q_m. The weighting parameters w are used to rank the temperature, pressure and steam mass flow according to operational requirements. Minimization of the objective functional, using the dynamic model (1) and taking into account the constraints (2)–(4), yields optimum trajectories for the control variables (fuel mass flow q_{mF}, HPB-valve position Y_{HPB}), such that the optimization objective is achieved. Besides the constraints related to thermal stress in certain plant components (4), there are many other constraints that exist in practice, and which have to be considered. For example, there are limits (2), (3) to the amplitudes of the control variables ($q_{mF,\min}$, Y_{HPB}), which may only vary at predefined

4 Typical layout of an operator interface for BoilerMax



maximum rates of change (2). Also, the oil fuel input q_{mF} depends on the number of available burners. Moreover, a minimal fuel input must be guaranteed to ensure safe combustion and a minimum warm-up. Changeover from oil to coal may depend on whether coal mills with the required capacity are available. This in turn can depend on the warm-up air and its temperature. And the combustion chamber temperature may have to be controlled as a function of the steam mass flow so as to prevent the tubes from overheating.

These, and other, constraints can be taken into account in a way which is both simple and transparent. The fact that they are an intrinsic part of the resulting optimized control variables is a considerable advantage; conventional solutions often require extensive modifications to the control system's function charts when constraints change.

Transparent control

All of this results in a very transparent automation structure. Referring again to 1, it is seen that the solution to the optimal control problem is calculated totally by BoilerMax. All the necessary signals (eg, thermal stresses, pressures, temperatures and valve positions) are received here from the steam generator system. The calculated optimized control variables serve as reference variables for the conventional secondary controllers, which can be left unchanged for the start-up. Responsibility for assigning the setpoints passes to other, higher-order controllers once the start-up phase is over.

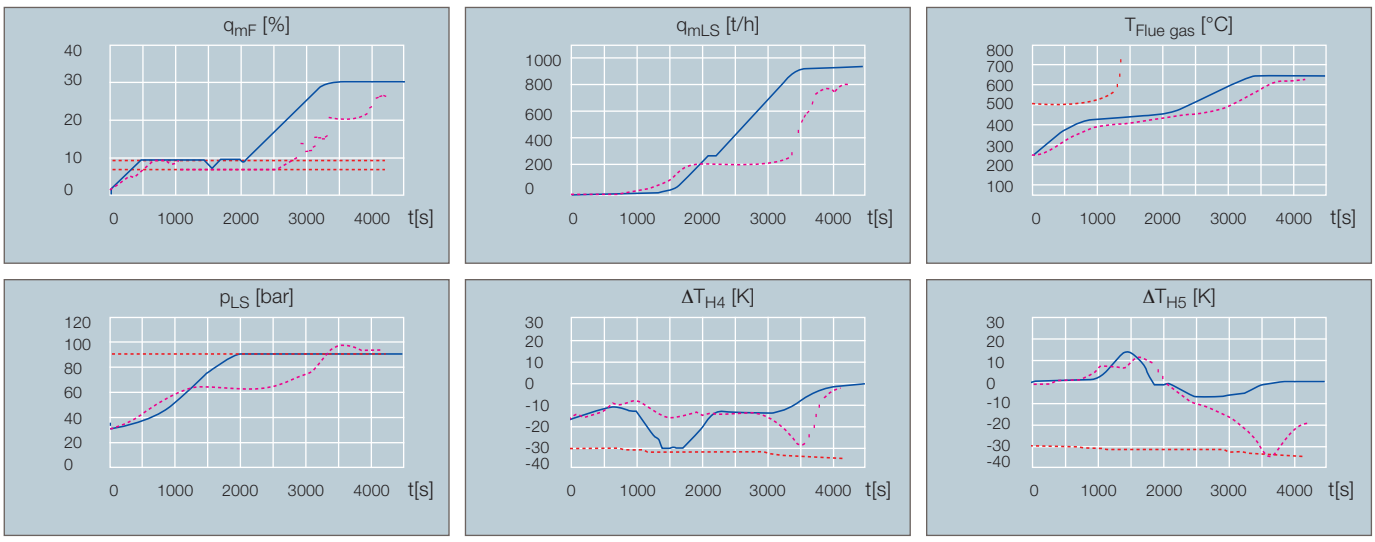
> Dynamic optimization has the great advantage that it allows existing constraints to be taken into consideration, a feature that most other approaches lack.

The optimization solver should preferably have its own, separate computer. There are two reasons for this: On the one hand, optimization is very time-consuming because of the predictive calculations that are required. And on the other, it makes it easier to embed the solver in existing automation systems, assuming a standard means of communication is used.

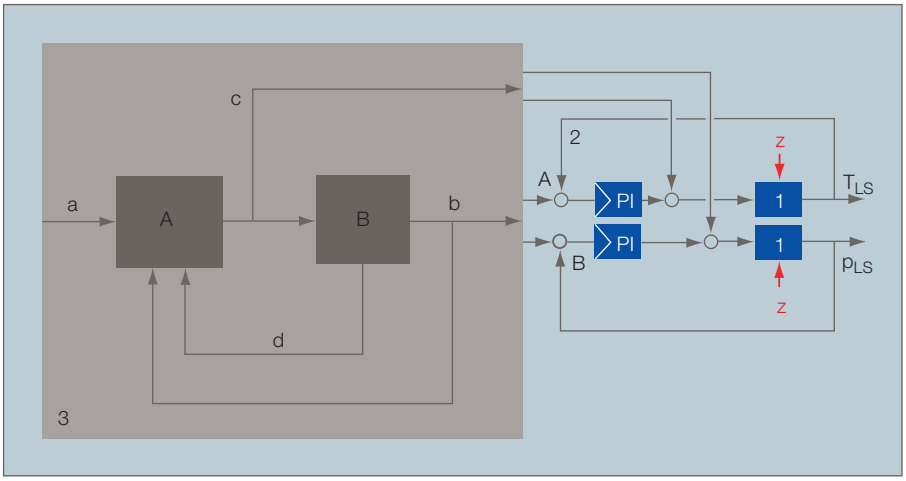
BoilerMax is connected via OPC, a standard protocol for reading and writing process values. For the pilot version, it was decided to also add a PROFIBUS connection 3. The DCS (Distributed Control System) communicates via the PROFIBUS interface with BoilerMax. This ensures that BoilerMax is embedded in real time. The calculated reference values are sent at a rate of one every five seconds to the subordinated controllers responsible for the fuel flow and HPB position and pressure. As an example, 4 shows the optimization task embedded in the (Maestro) operator station of the existing DCS.

At this point, it is interesting to compare the characteristics of a conventional start-up (magenta lines in 5) with those of an optimized start-up using BoilerMax (blue lines). In each case the start-up follows a shutdown lasting approximately seven hours. From an operator's point of view, this particular conventional start-up can be considered to be

5 Conventional start-up (magenta), proposal for an optimized start-up (blue) and some important limits (red)
Sampling rate: 1 minute Firing starts at t = 0



6 Block diagram of the closed-loop NMPC used for BoilerMax



1 Boiler system
2 Conventional control
3 BoilerMax/NMPC

A Optimizer
B Boiler model

a Target setpoints
b Current setpoints (references for secondary controllers)
c Feedforward control
d Internal variables
z Unknown disturbances

really good. The optimized control variable characteristics were calculated based on initial conditions comparable with those during the conventional start-up. These curves demonstrate convincingly BoilerMax's ability to optimize the control variables such that the thermal stress limits are not violated and the start-up time is shortened. Overall, the start-up phase is improved.

Some important limitations are marked in 5 in red. In the case of fuel input q_{mF} (for fuel oil), these are a minimum value of 6.5% and a maximum value of 9%. In the case of chamber temperature $T_{Flue\ gas}$, the upper limit (500 °C with zero steam flow) is shown as a function of the steam flow. The live-steam pressure p_{LS} is not allowed to exceed the target value of 90 bar. The maximum permissible temperature gradients of ΔT_{H4} and ΔT_{H5}, which depend on the steam pressure, are also plotted.

There are three arguments in favor of the optimized start-up. The mass flow and live-steam pressure reach their setpoints faster than during the conventional start-up. The turbine can be connected to the grid 15 min earlier, corresponding to an improvement of about 20%. And the thermal stresses are easier to control because their maxima lie in the oil-firing rather than the coal-firing phase. (It was necessary during the conventional start-up to delay the supply of fuel from the third coal mill in order to avoid thermal stress violation in ΔT_{H5}, and this caused the live-steam pressure limit to be exceeded.)

The NMPC as an extension of dynamic optimization

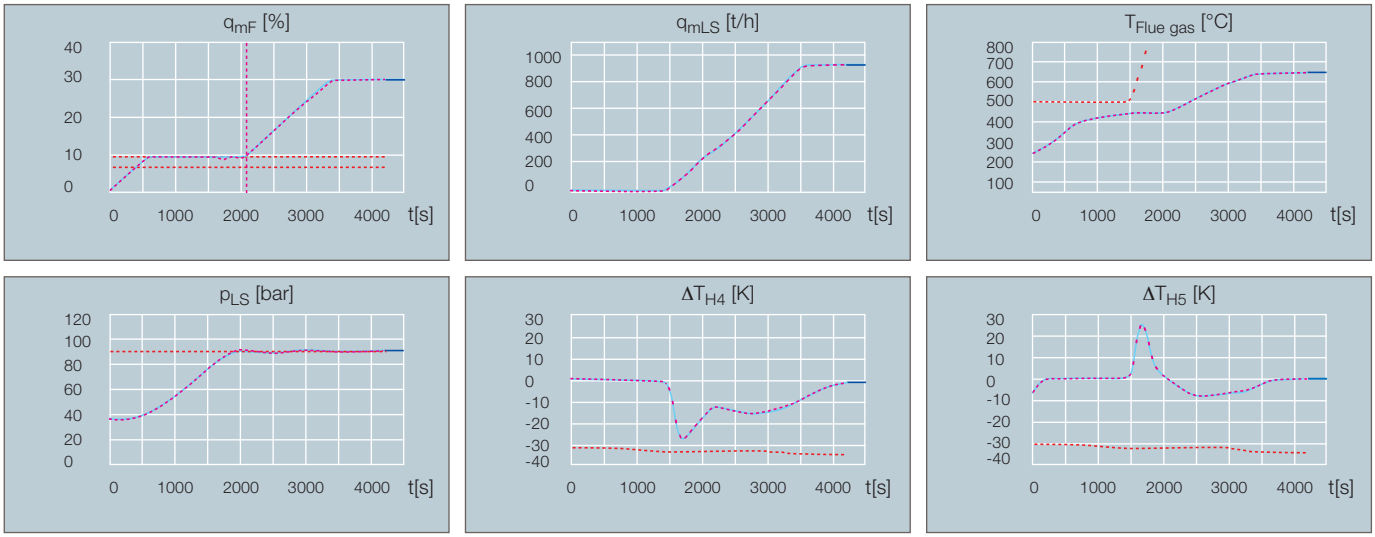
In addition to the described open-loop start-up strategy, BoilerMax also supports a closed-loop start-up. A precondition of the open-loop solution is that the optimized control variables influence the steam generator process exactly as predicted by the calculations, and as long as there are no disturbances this will also be the case. However, difficulties arise when unforeseen disturbances, such as burner failure, occur during start-up. Then, the optimization has to be repeated. The newly optimized control variables take the new conditions into account. If the optimization is carried out frequently enough, all changes or disturbances occurring in the steam generator system will be taken into account and the system can respond accordingly. So, what began as optimal open-loop control has now become optimal closed-loop control. Among control engineers, such an arrangement is referred to as a model-based predictive controller (MBPC, or MPC). Since the dynamic mathematical steam generator model used in the optimization is non-linear, with multiple inputs and outputs, this particular type is called a non-linear model predictive controller (NMPC). BoilerMax can handle both methods, one-time optimization of the control variables for a start-up (open loop) as well as repetitive optimization in the form of an NMPC (closed loop) 6.

> It is expected that the NMPC solution currently installed in a large power plant shut down and restarted 150 times a year will allow a 10% saving in start-up costs.

Steam generators – pushing the limits

Controls using this predictive functionality have proved to be a good investment in the petrochemical industry, among others. Here linear MPCs are

7 Start-up simulation with NMPC. The vertical dotted line in the first graph marks the point where the coal mills are ready to start. Afterwards, fuel input increases, changing from oil to coal.



most often used. ABB offers the 3dMPC for these applications.

For steam generators, a non-linear MPC had to be developed. Compared with a linear MPC this has to satisfy special requirements regarding the optimization solver and the system model; for example the very non-linear water/steam table has to be considered. Optimization in real time, in particular, called for an especially innovative solution [3].

The results of a start-up using the developed BoilerMax NMPC are shown in 7. Comparing them with the results for the conventional start-up in 5, it is seen that not only are the thermal stress limits kept to but that an even faster start-up is possible. To put this performance (900 t/h steam approximately one hour into the start-up) into perspective, we can consider again the coffee maker we mentioned earlier, and to which we likened the steam generator. An equivalent performance by the coffee maker would entail its reaching its operating temperature in the blink of an eye, and without breaking down!

Reduced start-up costs

BoilerMax is currently in use in a coal-fired power plant rated at around 700 MW_{el}. On average, this plant is shut down and restarted 150 times a year. It is expected that the installed solution will allow a 10% saving in start-up costs, as well as compliance with the thermal stress limits for selected critical components. Although these limits were not greatly exceeded using the conventional solution, BoilerMax will allow them to be kept to with a very high accuracy, thereby avoiding any negative impact on the plant's lifetime.

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