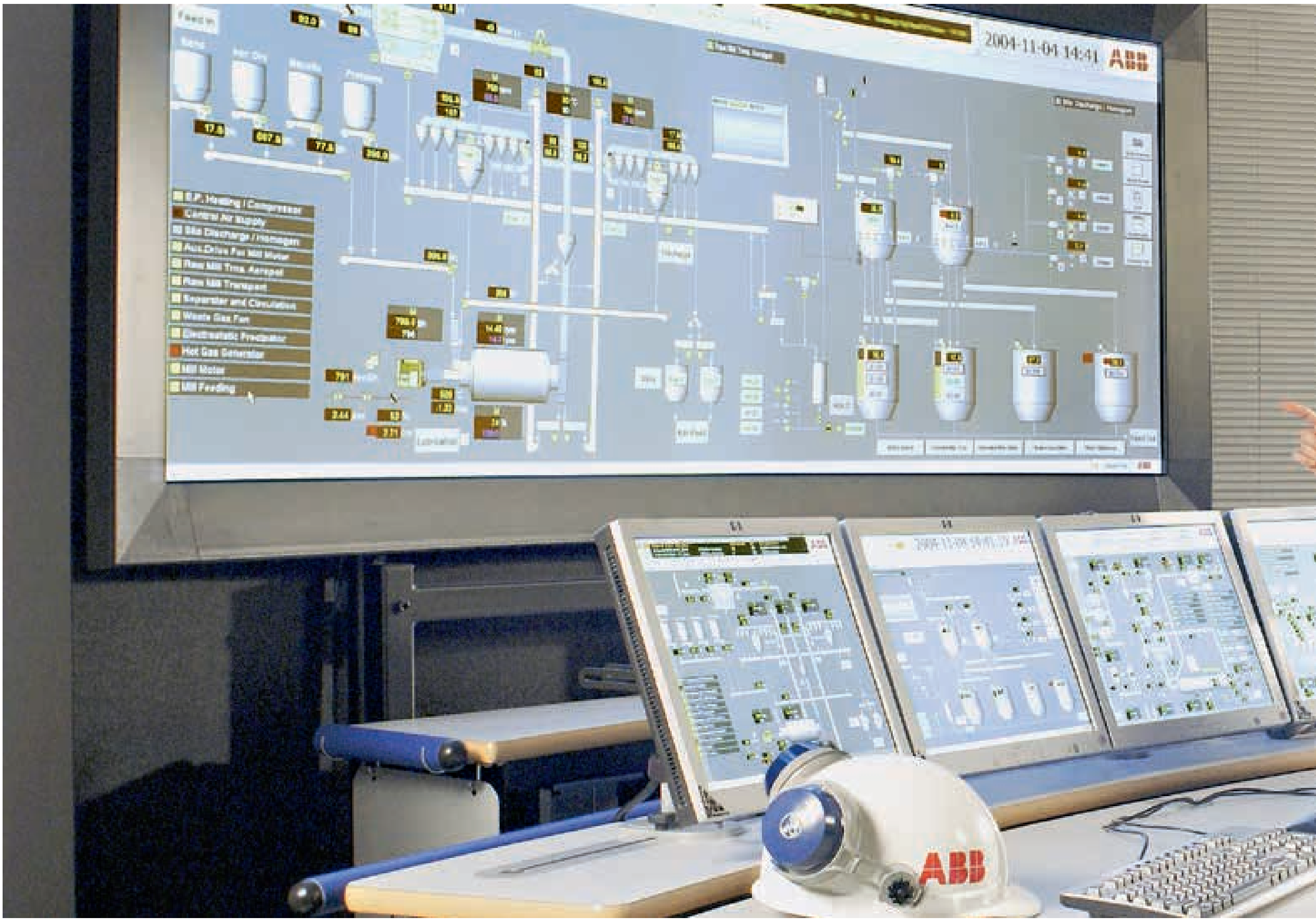


Advancing System 800xA

Demystifying MPC and how to deploy it with ABB's Extended Automation System 800xA

EDUARDO GALLESTEY, MICHAEL LUNDH, TOM ALLOWAY, RICCARDO MARTINI, MICHAEL STALDER, RAMESH SATINI – Model predictive control (MPC) is a well-established technology for advanced process control (APC). Its roots can be traced back to the 1970s [1, 2]. This technology has the proven ability to provide control solutions using constraints, feed-forward, and feedback to handle multivariable processes with delays and processes with strong interactive loops → 1. These types of control problems have successfully been handled in many industrial applications [3].

Optimization is an inherent capability in an MPC controller.

Using MPC brings many benefits. For example, there is less variation in process variables (PVs), which allows set points to be chosen that are closer to performance boundaries, which in turn leads to an increased throughput and a higher profit. MPC brings a structured approach to solutions that would otherwise consist of combinations of feed-forward and feedback with PID (proportional integral derivative) controllers, possibly with override functions.

Additional benefits of MPC are:
- Increases in process knowledge (estimation of hidden variables)
- Higher levels of automation, freeing operators to focus on more important tasks
- Extended scope of control strategy for optimization of, for example, specific energy consumption

Title picture
MPC automates many control room functions, freeing operators to focus on more important tasks.

Optimization is an inherent capability in an MPC controller → 2. Examples are often found in blending, mills, kilns, boilers and distillation columns.

MPC technology

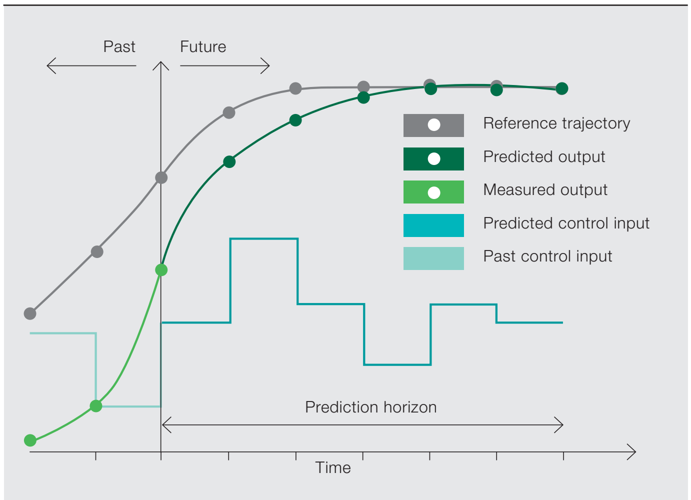
From a user perspective, the main components in an MPC are:

MPC reduces variation in process variables in many industrial applications, which in turn leads to an increased throughput and higher profit.

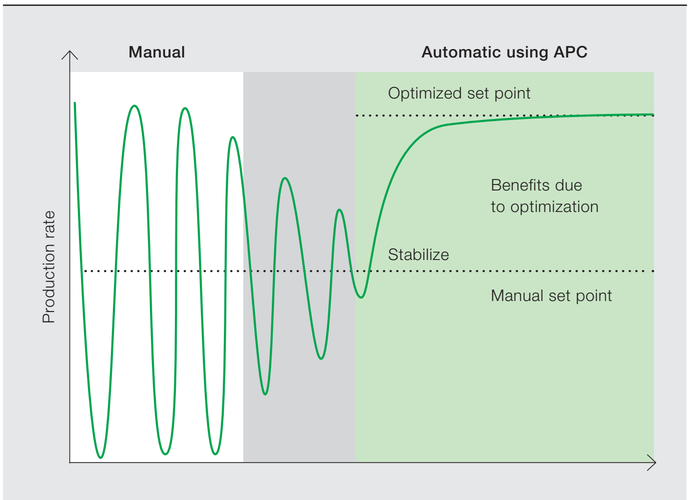
- The plant model
- An objective function
- A state estimator
- An algorithm for solving constrained optimization problems

The following actions take place on a cyclic basis and are repeated with equidistant intervals, of which the sampling time is chosen with respect to the time scale of the controlled process:
- The actual state of the process is estimated from current and past measurements and from the state at previous sample(s) using a state estimator. Kalman filters and moving horizon estimators are well established methods for this. The estimated state $\check{x}(k)$ is assumed to be an accurate approximation of the sometimes unmeasurable state in the true process. It is used as the starting point for the optimization in the next step.
- The plant model can be used to predict the future trajectories of the plant outputs for a given sequence/

1 Past and future trajectories in an MPC

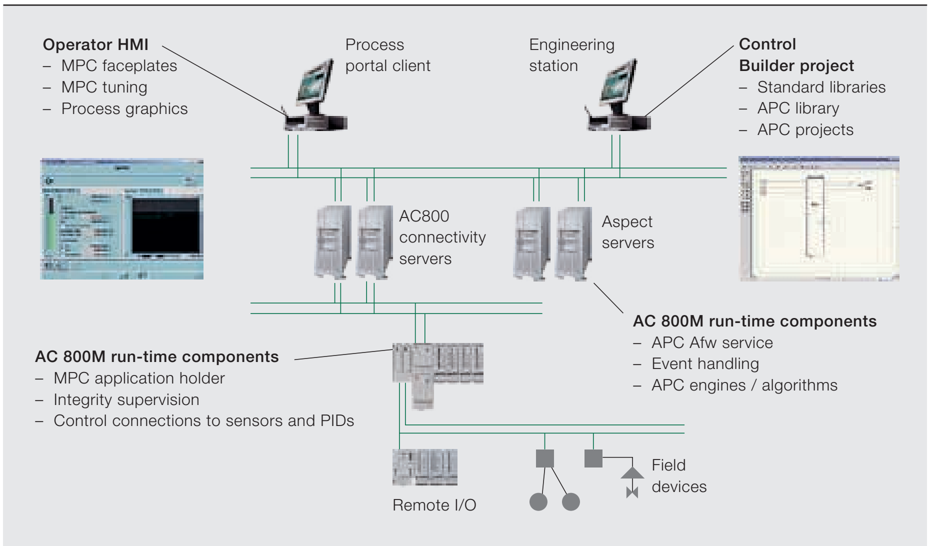


2 APC enabling optimization



Using the square form in the objective function serves to make the control problem "well behaved."

3 System 800xA APC overview



trajectory of future control signals. Optimization determines the future control signal such that the objective function is minimized. The optimization may also account for constraints on the process inputs and the process outputs.

– Finally, the first instance for each calculated future control signal is applied to the process.

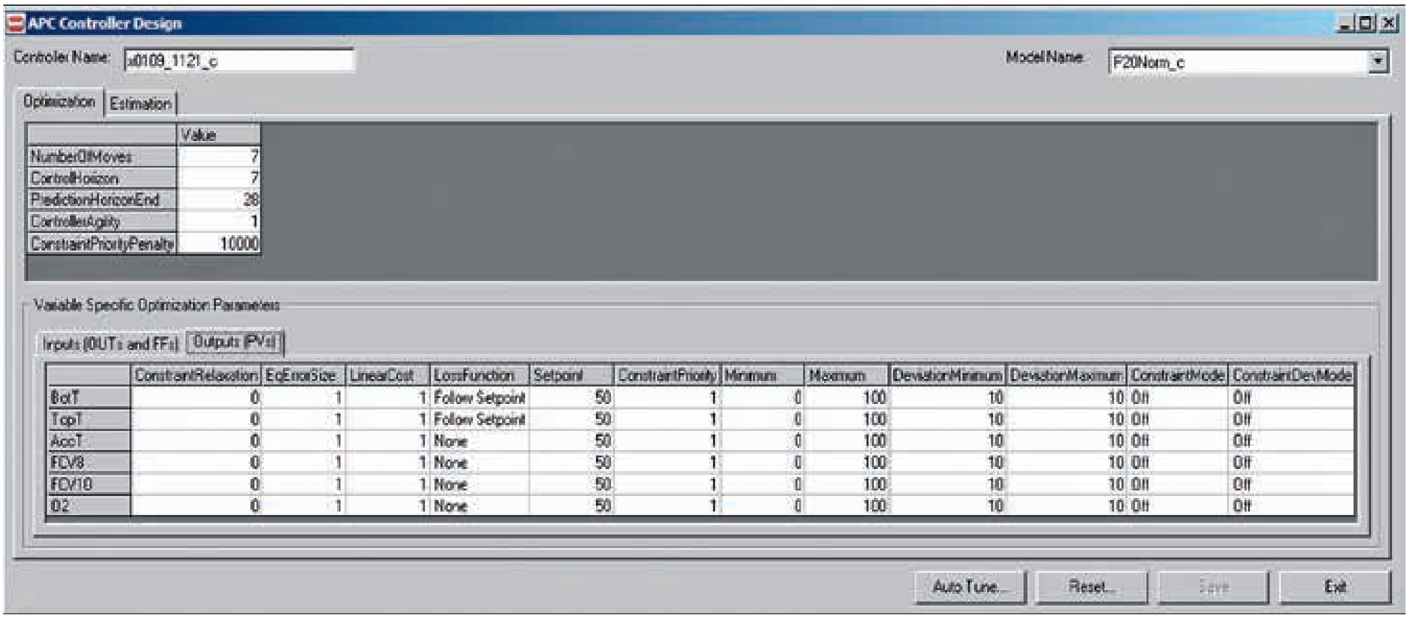
It is worth noting that normally the objective function is a weighted sum of deviations in the plant outputs and in the control signal increments. There may also be linear terms for minimization or maximization of certain variables. Using the square form in the objective function serves to make the control problem "well behaved" .

Traditional implementation of MPC

MPC has been utilized for process control within ABB for a long time, initially using third-party solutions from other vendors. Later, solutions were implemented using the ABB products Predict & Control, and Expert Optimizer. Typically MPC provides set points for the underlying cascaded PID controllers. Common for these approaches has been that the MPC has been running on a separate server, which is not part of the DCS (distributed control system). Signal data is then normally exchanged with the DCS using OPC; measurements, consisting of PV and feed-forward (FF) variables, are sent to the MPC, and the MPC outputs, also called manipulated variables (MVs), are then sent to the DCS.

However, for these solutions to work, a number of additional signals need to be exchanged between the DCS and the

4 GUI for entering tuning parameters



MPC on the external server. These carry information, eg, about which level-1 PID controllers will accept a set point from the MPC and whether the output from the PID is saturated. It is also necessary to move data between the MPC and the operator displays. Further information that needs to be exchanged is the status of the MPC, where often a "heartbeat" signal is used to indicate that the external MPC is alive. All of this communication needs to be configured before the engineer has even started to deal with the control problem. This must also occur before deciding to add or remove signals from the MPC. There is no question that the threshold to use MPC has been substantial.

Advanced process control in 800xA

The new product, System 800xA APC, is am MPC controller fully integrated in Extended Automation System 800xA → 3. It is available as a system extension. In addition there is a tool, the Model Builder, for modeling, controller tuning, and simulations.

In System 800xA APC there is a control module for an MPC controller in the AC 800M controller. Using this control module the MPC controller is easily connected to measured signals and to downstream PID controllers. Once this is done, and the application is downloaded to the AC 800M controller, the MPC can be operated manually using preconfigured operator displays and faceplates. The connections between the MPC and the other objects are established using "control connections." These are bidirectional multi-signal connections where not only signal values are transported but also the Boolean information about operational modes for the downstream PID.

System 800xA APC utilizes the 800xA infrastructure fully. Since an MPC controller can be computationally demanding the execution of the APC service for the MPC engine can be distributed to any server in the 800xA system. If desired, eg, for additional reliability, a redundant service can also be configured. Further, the System 800xA infrastructure provides all the necessary supervision, and all events and anomalies are recorded in the 800xA alarm and event functionality.

Other benefits of the System 800xA APC are:

- Built on already established ABB products
- Migration path for Predict & Control (P&C) and Expert Optimizer controllers
- A structure for the MPC application is enforced, which simplifies maintenance since all related artifacts are stored in one location

With this new product the control engineer can now concentrate on the control problem, leaving all other issues to the platform.

Configuring System 800xA APC

The MPC controller is packaged as an 800xA system extension with a library and a service. Configuration of an instance of the MPC controller in the 800xA APC starts in the 800M Control Builder. After connecting the PVs (measurements), MVs (controller outputs), and FF variables (measurable disturbances), the application can be downloaded to an 800xA controller. Normally the MPC MVs are connected to external set points for cascaded level-1 PID controllers.

The following has then been accomplished:

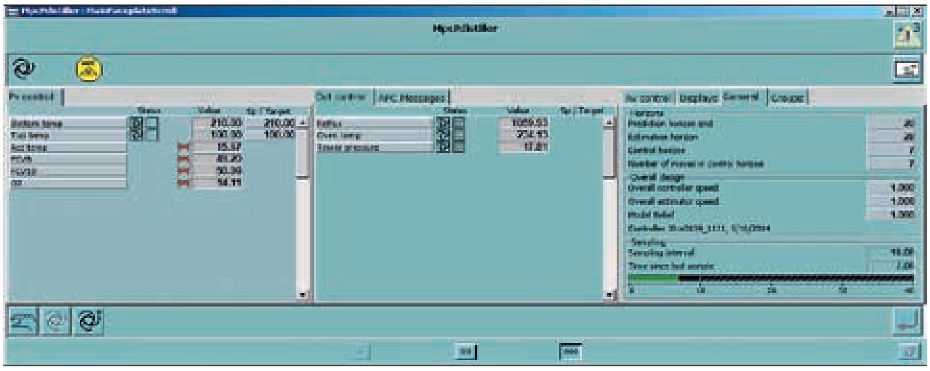
- The MPC can be operated in manual mode from faceplates. All signals can be visualized in faceplates. This is useful, for example, for plant testing to obtain data for empirical modeling.
- Supervision is automatically established for the data transfer between the control module and the 800xA service with the MPC engine.
- By using control connections between the MPC and the cascaded PID controllers the MPC will notice when a PID is not operating in auto mode with an external set point, and the MPC will also notice when signals in the PID saturate. The MPC is then able to take the correct actions when such situations occur.

Modeling and controller design

The Model Builder is intended for, as the name indicates, creating the model that will be used in the MPC. The model can be created in three different ways.

The System 800xA infrastructure provides all the necessary supervision, and all events and anomalies are recorded in the event and alarm functionality.

5 Main operator faceplate



One way is that a model can be obtained using empirical modeling, where a discrete time-state space model is calculated from logged data. Data should preferably be obtained from an identification experiment where the MVs are changed up and down. There are different ways to do this; the simplest is to make step changes in each of the MVs sequentially.

Alternatively a model can be defined by a set of low-order transfer function models, one for each input-output relation in the multivariable model. A typical low-order transfer function is defined by the parameters in:

$$G(s) = \frac{K}{sT + 1} e^{-Ls}$$

but more complicated transfer functions can also be defined.

A third possibility is to graphically build a first-principles model using predefined blocks. This is the most generic method that is supported in the Model Builder.

Control engineers can concetrate on the control problem leaving all other issues to the platform.

Although these are completely different approaches, a model can be merged together by using smaller models of any of the three types.

The Model Builder provides functions to analyze models. There are functions for step responses and also for model validation where the model is fed with logged inputs and the simulated model outputs are compared with logged outputs.

Once a model is considered to be of sufficient quality for use in the controller, an MPC can be designed. This is also done in the Model Builder. Design parameters are entered in a table → 4. An auto-tuning feature is available to provide initial parameters for less experienced users.

The influence of the chosen tuning parameters can be evaluated by simulations with different inputs. There are possibilities for simulation with steps in set points, in feed-forward, and in output disturbances. Robustness can easily be evaluated when using a different model for simulation than the one that is used in the MPC controller.

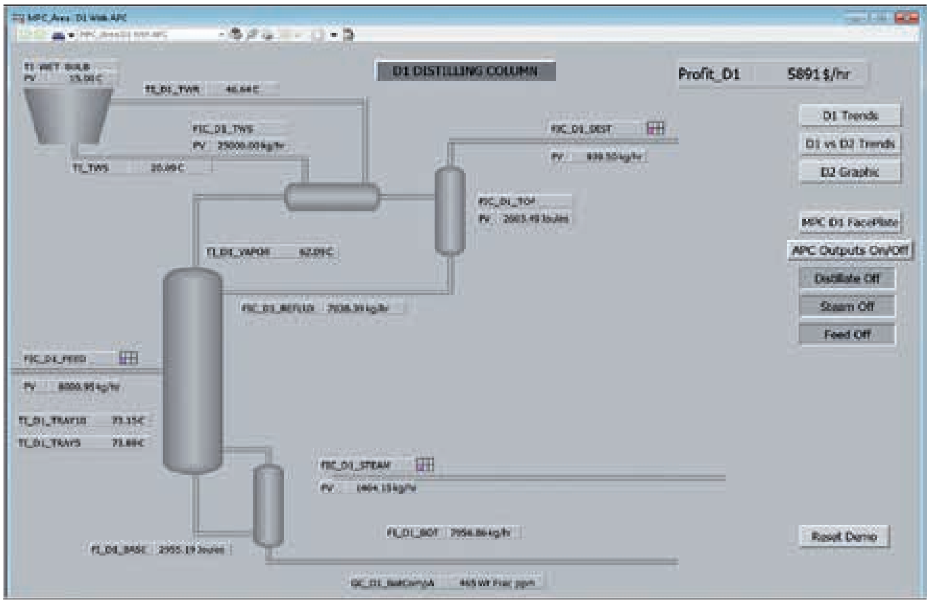
The controller parameters are stored together with the model as an xml file.

MPC commissioning in System 800xA

The final step is to deploy the designed MPC in the 800xA system. In System 800xA Plant Explorer an xml file, with tuning parameters and model, can be selected to configure the online MPC algorithm with one of the MPC controllers that was defined in the Model Builder. Now the MPC controller is fully operational in the 800xA system and can be switched to auto mode to fulfill its task.

Once the basic configuration is finished a number of tailor-made faceplates are generated by the system → 5. These faceplates contain complete information

6 Distillation column



Once a model is considered to be of sufficient quality for use in the controller, an MPC can be designed.

for both the operator and the APC engineer. In other words, not only set points and limits are available, but also the internal parameterization of the controller is accessible to authorized 800xA users.

Most of the tuning parameters are available in the faceplates provided or operator displays. This is useful if further online tuning is needed.

In cases where several APC controllers are deployed in the same server, it might be necessary to spread the CPU load. This is achieved using the scheduling tool provided by 800xA APC, where each controller is assigned a time slot for its optimal starting point.

Additional functionality is available due to the integration with System 800xA. For example, 800xA offers integrated alarm handling, National Language Support and APC key performance indicator (KPI) tables.

Typical use cases

There are five typical use cases for APC controllers.

Distillation columns in oil and gas

Distillation columns are widely deployed in the process industry. Their use is recommended when there is a need to separate components that have different boiling points. The main idea is to introduce the raw mix of components, usually in liquid form, into the middle section of the distillation column. Through successive vaporization and condensation steps the low boiling point components are concentrated at the top of the column and the high boiling point components are concentrated at the bottom. A typical example is the separation of crude oil into components such as gasoline, kerosene and diesel.

Since each step influences the others, the problem is naturally multivariable. However the process is highly repeatable and thus well suited to modeling via empirical or data-driven modeling. Typical process variables are temperatures, pressures and compositions at the different levels of the column, while the main actuators are feed, firing, reboilers for the column bottom, pump-around flows, cooling rates and overhead pressure control bypass → 6.

MPC projects in this field deliver better process stability, more homogenous quality of the components extracted at each step, and, depending on the customer business objectives, yield maximization, throughput increase, reduction of quality "giveaways," or minimization of energy consumption [4].

Grinding and flotation in the minerals industry

In a typical grinding circuit at, for example, a copper mine, the ore is introduced in the mills where abrasion, attrition and impact reduce its size. Usually, the grinding circuit contains at least two interconnected mills with material classifiers (eg, cyclones) separating the fine material from the coarse (that then goes for regrinding).

The process is very energy intensive with power consumption of roughly 20 to 30 MW and feed throughputs of 2,500 to 3,000 t/hr. Process variables are mill loads, motor torque and power, plus pressures and flow rates. The ground product is specified in terms of fineness range. The typical results of an APC controller → 7 are increased throughput, homogeneous product quality and lower maintenance costs.

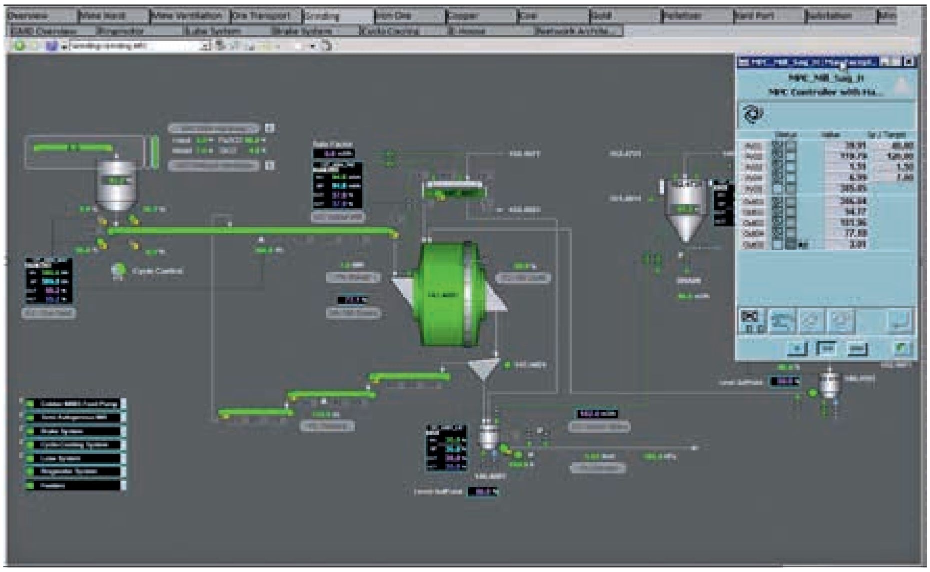
Further, APC can be advantageously deployed in the flotation plant, where the ground ore, now in slurry form, is "washed" to separate valuable minerals from waste. The goal being maximum production or maximum yield at a given concentrate quality, APC performs timely adjustments to froth levels, air flows and reagents leading to process stabilization and increased recovery [5].

Kilns in the cement industry

The rotary cement kiln process is intrinsically unstable, there are long time delays and large perturbations acting on it. The control problem consists of maintaining a given temperature profile along the kiln plus obtaining good burning conditions. Further, the control strategy needs to achieve that at the lowest energy consumption possible, which means riding along constraints such as amount of air in the exhaust gasses. The problem ex-

An auto-tuning feature is available to provide initial parameters for less experienced users.

7 Minerals grinding application



hibits relatively long time delays related to the slow transport of the raw meal along a series of heat exchangers, cyclones and then the kiln.

Actuators are kiln speed, energy input (fuels), air and feed, while the process parameters to be controlled are temperature in the kiln front (or specially built soft sensor thereof), temperature at the kiln inlet, and oxygen in the gasses traveling through the system. Additional complexity might also come from the usage of alternative fuels, where the control strategy needs to calculate the optimal fuel mix for the given conditions.

The typical benefits a user can expect to achieve from using System 800xA APC for cement kiln optimization (branded as "Expert Optimizer") are increased output, lower fuel consumption, longer refractory life and better and more consistent quality [6, 7].

Continuous pulp digester

The Kamyr continuous pulp digester is a complex tubular reactor where wood chips react with an aqueous solution of sodium hydroxide and sodium sulfide (referred as white liquor) to remove the lignin from the cellulose fibers. The product output from the digester is cellulose fibers or pulp. Most continuous digesters consists of three basic zones: an impregnation zone, one or more cooking zones and a wash zone. The white liquor penetrates and diffuses the wood chips as it flows down through impregnation zone. The mix is heated to a target cooking temperature where bulk delignification starts, and the majority of lignin is removed. The cooking process is stopped at the beginning of the wash zone by reducing the temperatures and cooked pulp is washed in a counter-current washing zone, using wash liquor injected at the bottom of the digester.

Producing an even quality pulp at a consistently high production rate is a challenging task for digester operators where the raw material quality, such as chip size and chip moisture, tends to change with the seasons, natural geographic factors, and the wood source. The schedule also swings from hardwood to softwood making the process control task more complex.

At the core, advanced control package for the digester (known as OPT800 Cook/C, an application built on the System 800xA APC platform) stabilizes pulp production, reduces chemical usage and coordinates the numerous loops to incur optimum, on-specification, pulp quality at minimum variance. This optimum pulp quality production assures the minimization of bleaching chemical use where bleached grades are produced. In addition, these controls maximize production, yield, and paper stock drainage on the paper machine in both bleached and brown product mills. The process variables includes blow kappa number, digester level, residual alkali concentration and the production rate. The product quality is specified in terms of Kappa target, and level range.

The exemplary results from recent installation indicates a 51% reduction in blow kappa number, a pulp quality indicator with a stable blow flow rate, and a 60% reduction in chip level variation in the digester. Stabilized chip movement leads to stable residence time in the different zones of the digester [8].

Industrial steam power plant

In several process industries (oil and gas, pulp and paper, minerals, etc.) production requires both steam and electrical power. In these cases, plant operators often build in an in-situ utility unit to satisfy these needs. These are not mainstream power plants like those normally built for power generation. Indeed, not only is the steam needed at different, very specific pressures and temperatures, but its consumption rate is also highly variable due to the variability of the process conditions, trips and/or starts of steam consumers, etc. It follows that steam network stability and reliable power output are difficult to attain. In some cases, steam is generated also via energy recovery from other units eg, furnaces in a steam cracker or from byproduct gas usage eg, blast furnace gas for a steel manufacturing plant. This introduces further disturbances to the steam network as energy and fuel recovery is subject to upstream unit's availability and cycles.

Typically the foremost important goal is delivering enough steam, at the required parameters, to the process while producing as much power as economically optimal at a given market conditions. In

8 Steam temperature stability with and without APC

other configurations, the problem might also comprise delivering heat to a district heating system.

Further complexity is added by energy market variables, prices, and local rules for energy markets. In addition to that, internal incremental production price depend on variable fuel block prices. It follows that in many cases the optimal power output is very different between peak and low energy prices and thus re-positioning of the power production is needed. For instance, when the real time energy price is below the internal production price the tie line import is maximized. But when the real time market price is higher than the internal price, the tie line is minimized.

From an APC point of view, typical actuators are boiler rates, steam turbine inlet/extraction rates, gas turbine MW targets, attemperators, pressure control valves, steam flows to users and vent valves. There are multiple constraints and couplings, delivering a text book case where APC can outperform classical control schemes, typically based on cascades of PIDs and separate PIDs operating with staggered set-points.

Projects of this sort have been executed by ABB quite often in recent years and have delivered a more stable and reliable steam supply to the process with, reduced operating costs, higher energy efficiency ➔ 8, higher average profit (eg, by selling more at higher price and less at lower price) and lower disturbances to the power plant and energy users [9].

Advanced outputs

This is a new extension to System 800xA, leading to straightforward design and deployment of APC in ABB's 800xA DCS: 800xA APC.

800xA APC cleanly splits the work related to modeling and control design from the more usual tasks of connectivity, safety locks, and HMI settings, which effectively happen in a configuration-free manner. The system also facilitates remote commissioning and application support.

The typical use cases in the cement, minerals, pulp and paper, and oil and gas industries cover the vertical industries where ABB has a strong footprint.

ABB continues to invest in this technology with the aim of increasing the value that the company's control system delivers to its customers, across the entire ABB global footprint. The optimization that is inherent to MPC brings not only financial benefits to ABB's customers, but contributes to an ongoing drive to reduce emissions, and resource use, which delivers benefits beyond the scope of the process under consideration.

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