Improving Boiler Stability
Through Advanced Regulatory Control

Jacques Smuts, OptiControls, Inc., Houston, Texas

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ABSTRACT

Coal-fired power plants must be highly flexible and responsive to accommodate changes in power consumption. Regular feedback control alone falls short of maintaining boiler stability during these rapid swings in power demand. A popular solution for improving the controllability of large power boilers is the use of advanced regulatory control (ARC) strategies in addition to simple feedback control. Modern control systems support the building blocks of ARC strategies as standard functions making them straightforward to implement and optimize.

This paper describes the application and optimization of several ARC techniques for improving the control performance of large coal-fired power boilers during load transients. Various boiler control subsystems are described, the limitations of feedback control only are discussed, appropriate ARC strategies are introduced, and steps for design and optimization of these strategies are given.

INTRODUCTION

While nuclear and renewable power plants are normally run at their maximum generation capacity, fossil fuel-fired power plants are ramped up and down to accommodate the hourly changes in power consumption, and to provide minute-by minute frequency control for the power grid. Many coal-fired power plants were originally designed for steady, base-load operation, but because of economic changes and environmental pressures, these plants now operate in dynamic, load-following mode, requiring them to be highly flexible and responsive to changes in power demand.

Regular feedback control alone falls short of maintaining boiler stability during these rapid swings in power demand. Coal-fired power plants, originally designed for steady-state operation, but now loaded cyclically, often experience boiler control problems resulting from the highly interactive boiler subsystems, long time lags, inherent nonlinearities, rapidly changing load set points, and wide operating ranges.

Although advanced process control (APC) technologies hold promise for improving the control of boilers [1][2], the power industry has been slow in adopting it (Figure 1), citing economic justification as the leading barrier to implementation. Yet boiler control challenges continue, and low-cost solutions implemented within existing distributed control systems (DCS) remain more attractive for the cashstrapped power industry. Modern control systems provide the building blocks for ARC strategies as standard functions that are straightforward to implement and optimize.

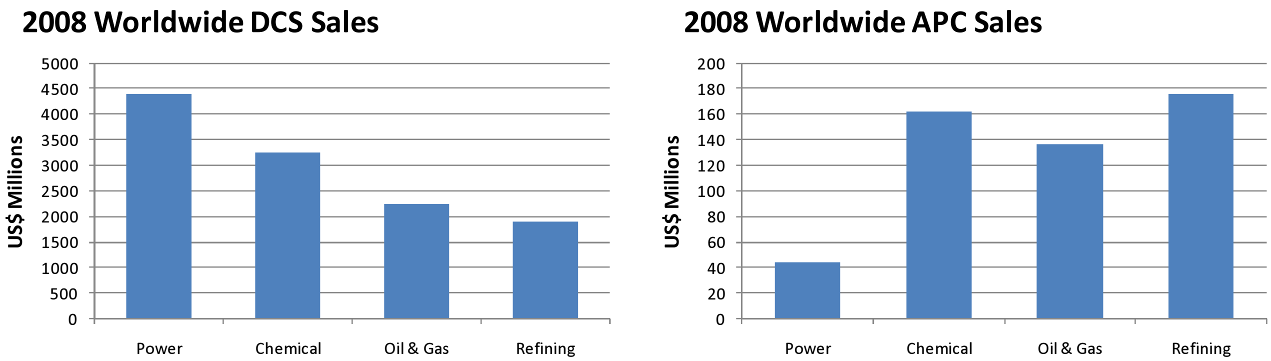

Figure 1. Relative to DCS sales, the power industry lags behind other major industries in adoption of APC. Adapted from [3] and [4].

This paper describes the design and application of several ARC techniques for improving the control performance and stability of large coal-fired power boilers during transient operation. Various control subsystems are described, the limitations of feedback control only are discussed, appropriate ARC designs are introduced, and steps for optimization of these systems are given.

Although drum-type power plant boilers are the target process of this paper, the ARC techniques described here apply to other types of processes as well.

MAIN BOILER CONTROL LOOPS

The steam generation process may seem simple at a high level, but boiler control designs quickly become complex when all the subsystems and their interactions and dependencies are considered. The main control loops in a boiler control system are listed below.

1. Boiler Drum Level and Feedwater
2. Furnace Pressure
3. Steam Temperature
4. Generator Load
5. Throttle Pressure (Steam Pressure)
6. Fuel Flow
7. Air Flow
8. Excess Air (Oxygen in Flue Gas)

The first five control loops listed above are discussed below to illustrate the application of ARC strategies for improving control loop stability and performance. The last three loops listed above and many second-tier boiler control loops can also benefit from advanced control strategies. The concepts discussed in this paper apply to them too.

DRUM LEVEL AND FEEDWATER CONTROL

Boiler water circulates through the evaporator tubes lining the furnace walls (also called water walls) where it is partially converted to steam. The water-steam mixture returns to the boiler drum where the steam and water are separated. The steam exits the drum, is superheated and flows to the turbine. To make up for the water lost as steam, feedwater is added to the boiler. The level of the boiler drum serves as an indicator of the balance between steam flow and feedwater.

Maintaining the boiler drum level close to its set point is critical - if the level becomes too low, the boiler can run dry resulting in mechanical damage of the drum, boiler piping, and boiler water circulating pumps. If the level becomes too high, water can be carried over into the steam piping, possibly damaging downstream equipment.

The design of the boiler drum level control strategy is normally described as single-element, two-element, or three-element control. The three designs are described below.

SINGLE-ELEMENT CONTROL (FEEDBACK CONTROL)

Boiler feedwater pumps supply water to the boiler. The feedwater flow rate is controlled by feedwater control valves on the discharge side of the feed pumps. The water level in the drum is measured with a pressure and temperature-compensated level transmitter. The drum level controller compares the drum level measurement to the set point and modulates the position of the feedwater control valves to keep the water level in the drum as close to set point as possible. Variable-speed boiler feed pumps are sometimes used to control the level instead of valves.

The simple feedback control design described above is called single-element control, because it uses only a single feedback element for control – the drum level measurement (Figure 2).

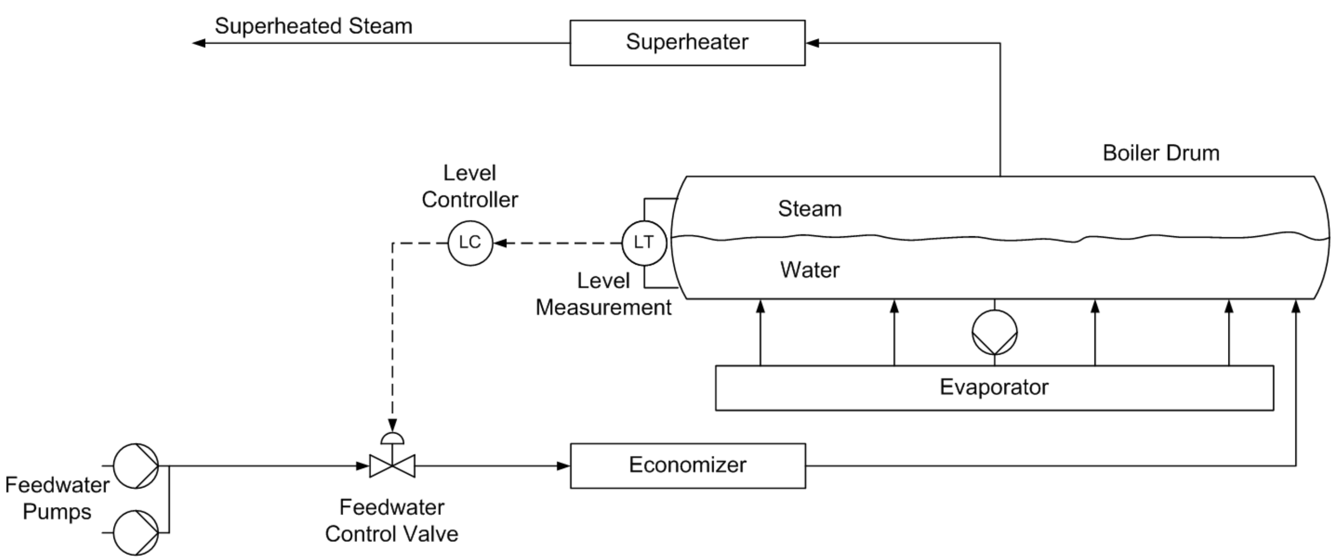

Figure 2. Single-element drum level control.

TUNING CONSIDERATIONS

INTEGRATING PROCESS

From a controls point-of-view, the boiler drum is an integrating process. This means that any mismatch between inflow (water) and outflow (steam) will cause a continuous change in the drum level.

Integrating loops are difficult to tune, and can easily become unstable if the controller's integral time is set too short (i.e. high integral gain). This process-imposed requirement for a long integral time makes the loop slow to recover from disturbances to the drum level.

INVERSE RESPONSE

To further complicate matters, the boiler drum level is notorious for its inverse response. If the drum level is low, and more feedwater is added to increase it, the drum level tends to decrease first before increasing. This is because the cooler feedwater causes some of the steam in the evaporator to condense, causing the volume of water/steam to decrease; hence the drop in drum level.

Conventional feedback control has difficulty in coping with this inverse response. A control loop using a high controller gain and derivative action may work well in other level applications, but it can quickly go unstable on a boiler drum level. Stability is best achieved by using a low controller gain, long integral time, and no derivative. However, these settings make the controller's response very sluggish and not suitable for controlling a process as critical as boiler drum level.

MAJOR DISTURBANCES

Drum level is affected by changes in feedwater and steam flow rate. But because of the very slow response of the feedback control loop, changes in feed flow or steam flow can cause very large deviations in boiler drum level. Single-element drum level control can work well only if the residence time of the drum is very large to accommodate the large deviations, but this is seldom the case – especially in the power industry. For this reason, the control strategy is normally expanded to include feedwater and steam flow.

TWO-ELEMENT CONTROL (CASCADE CONTROL)

Many boilers have two or three feed pumps that can be switched on or off individually, depending on boiler load. If a feed pump is started up or shut down, the total feedwater flow rate changes. This causes a deviation in drum level, upon which the drum level controller will act and change the feedwater control valve position to compensate. As explained above, the level controller's response is likely very slow, so switching feed pumps on and off can result in large deviations in drum level.

A faster control action is needed for dealing with changes in feedwater flow rate. This faster action is obtained by controlling the feedwater flow rate itself, in addition to the drum level.

To control both drum level and feedwater flow rate, cascade control is used. The drum level controller becomes the primary controller and its output drives the set point of the feedwater flow controller, the secondary control loop. This arrangement is also called two-element control, because both drum level and feedwater flow rate are measured and used for control (Figure 3).

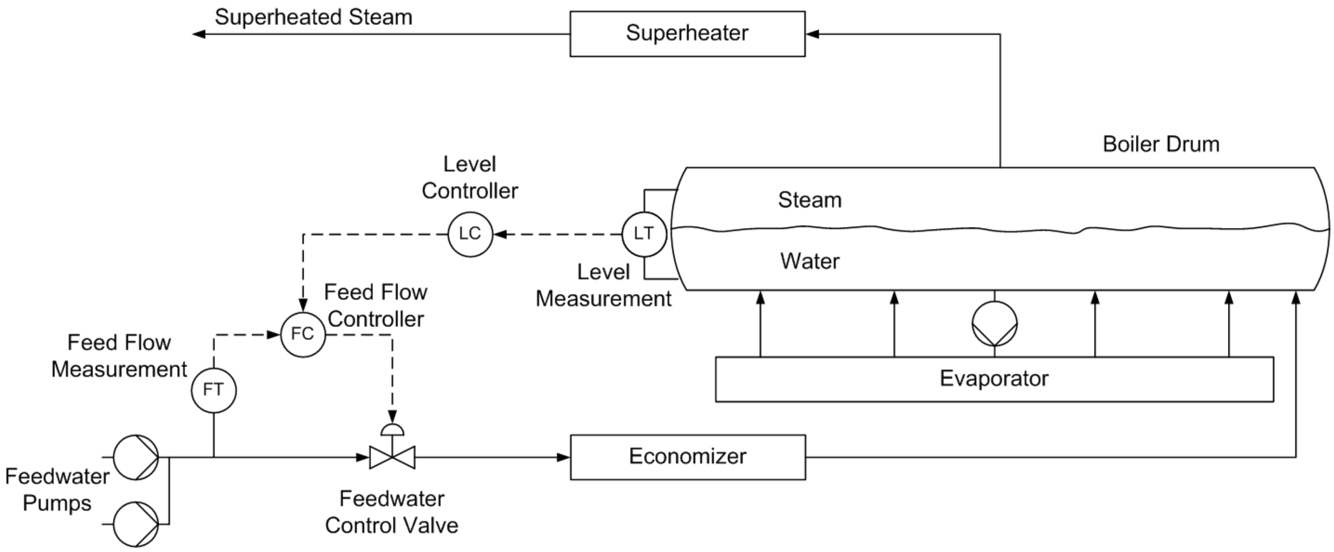

Figure 3. Two-element drum level control.

THREE-ELEMENT CONTROL (CASCADE + FEEDFORWARD CONTROL)

Similar to feed flow, changes in steam flow can also cause large deviations in drum level, and could possibly trip the boiler. Steam flow rate is measurable and can be used to improve drum level control very successfully by using a feedforward control strategy. The combination of drum level measurement, steam flow measurement, and feed flow measurement to control boiler drum level is called three-element control.

For the three-element control strategy, steam flow rate is measured and used as the set point of the feedwater flow controller. In this way the feedwater flow rate is adjusted to match the steam flow. Changes in steam flow rate will almost immediately be counteracted by similar changes in feedwater flow rate. To ensure that deviations in drum level are also used for control, the output of the drum level controller is added to the feedforward from steam flow (Figure 4).

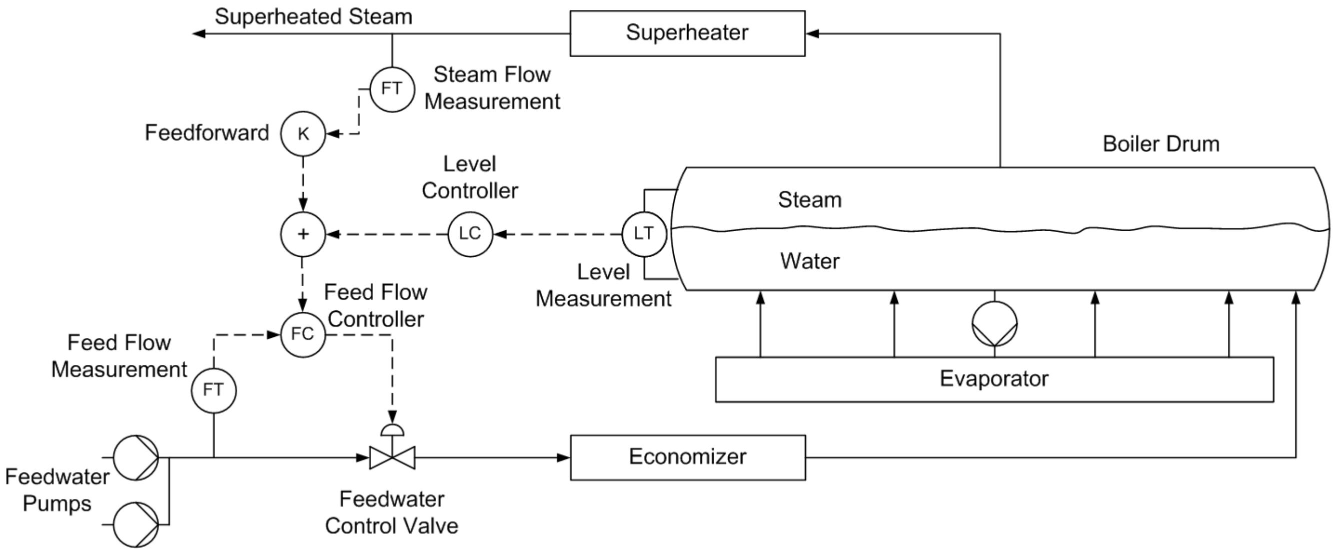

Figure 4. Three-element drum level control.

PRACTICAL ASPECTS OF THREE-ELEMENT CONTROL

Although three-element drum level control is superior to single- or two-element control, it is normally not used at low boiler loads. At low steam flow rates (for example during boiler start-up) steam and feedwater flow measurements are not accurate enough for three-element control, so then only the drum level measurement is used for control (single-element control.) Switching between single- and three-element control can be automatic or operator initiated, depending on the design of the control logic.

Boilers are normally fitted with a continuous blow-down system to get rid of any particular matter in the boiler water. So the ratio between feed flow and steam flow is not 1:1, but a slightly higher ratio. This ratio can be easily determined on a running plant, and the gain of the feedforward is set accordingly.

Another factor to consider is that of *shrink* and *swell*. With a decrease in steam flow and boiler firing rate, boiling in the water walls is reduced, and the water/steam mixture appears to shrink, leading to a decrease in drum level. Conversely, swell occurs with an increase in boiler load, resulting in an increase in drum level. Without any specific compensation for shrink and swell, the drum level controller will eventually bring the drum level back to set point.

However, a faster and more effective method of compensation for shrink and swell is achieved by placing a lag function in the steam-to-feed flow feedforward to delay the response of the feedwater [5]. Although the initial shrink and swell will still cause the drum level to deviate, a properly tuned lag will delay the feedwater response just enough that the level returns to set point without requiring any further control action.

CONTROLLER GAIN SCHEDULING

The feedwater control loop should be tuned for a fast response so that it rapidly rejects disturbances in feed flow and meets the demand of the drum level controller. The change in feedwater flow rate obtained from a given change in controller output depends on the number of feedwater valves in service. To get a consistent feedwater control loop response regardless of the number of feedwater control valves in service, it is necessary to implement gain scheduling. This will change the gain of the feedwater controller based on the number of feedwater control valves that are in automatic control (Figure 5).

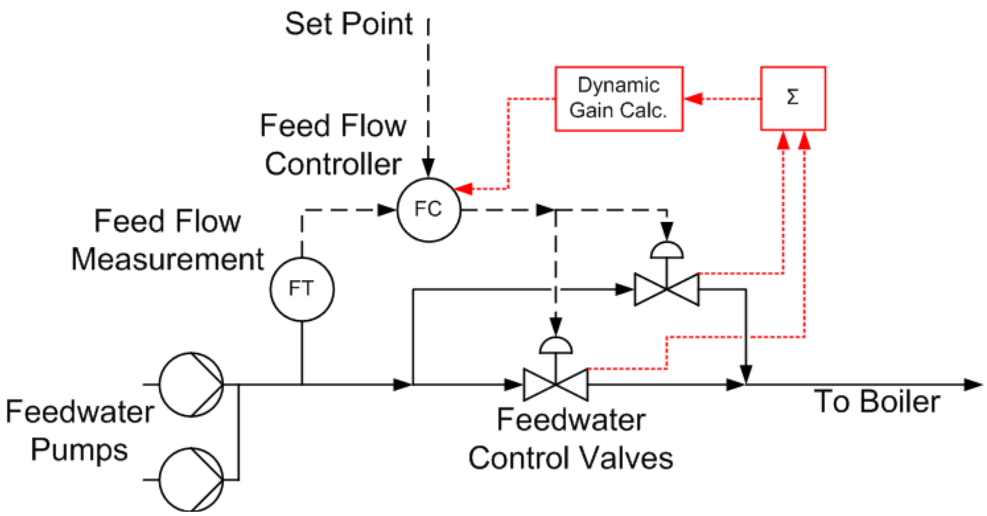

Figure 5. Feedwater controller gain scheduling.

The simplest way to design the gain scheduler is to tune the feedwater flow controller with one valve in service, and use that as the base gain setting. This setting is then dynamically divided by the number of feedwater control valves in service and running in automatic control mode. The resulting number is used as the final controller gain for the feedwater flow controller.

FURNACE PRESSURE CONTROL

Most large power plant boilers have two or more forced draft (FD) fans and two or more induced draft (ID) fans [8]. These will normally be run in pairs consisting of one FD fan and one ID fan. The FD fans force air into the furnace while the ID fans extract the post-combustion gasses from the furnace. Air flow rate through the fans can be manipulated with vanes, dampers, or by changing fan speed.

Air flow through the FD fan is controlled based a set point derived from the fuel flow rate and the air-to-fuel ratio. The flow through the ID fan is manipulated to control the furnace pressure. Furnace pressure is maintained at a slightly negative gage pressure (slightly below atmospheric pressure) so that fuel, ash, and flue gas won't escape through furnace inspection doors and other crevices.

Under normal operating conditions the furnace pressure acts like an integrating process. If there is a mismatch between draft in and out, the furnace pressure will change and continue to change until the high or low pressure trip point is reached. Consequently, the flow rates in and out of the furnace must be dynamically balanced so that the furnace remains close to its set point. A large deviation from set point will result in a boiler trip to keep the plant safe.

The furnace pressure controller changes the induced draft flow rate to keep the furnace pressure at its set point. If air flow rate is measured at the ID fans, a cascaded flow controller can be implemented for improved control (Figure 6). If air flow rate is not measured, the furnace pressure controller will manipulate the control element directly.

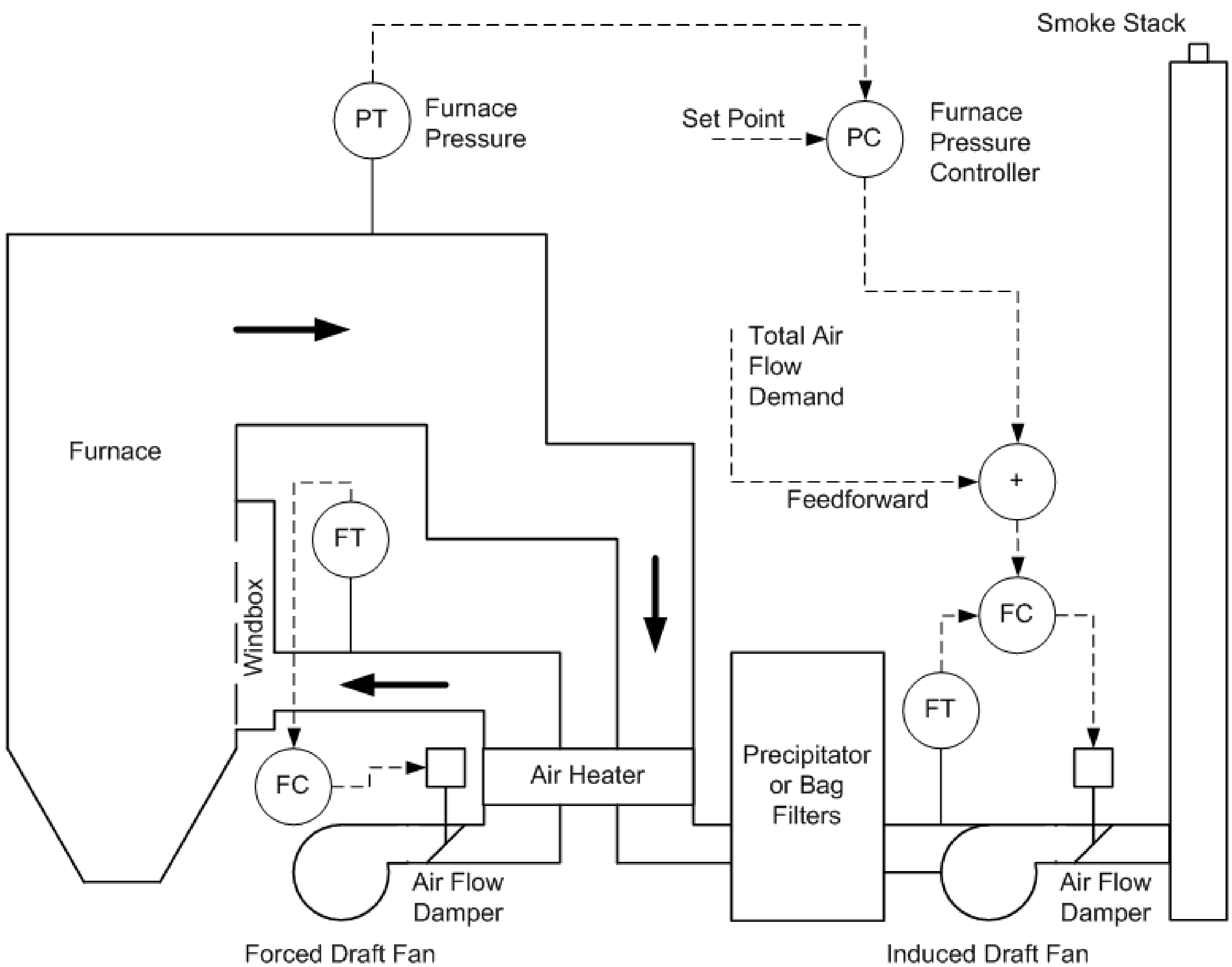

Figure 6. Furnace pressure control including feedforward.

FEEDFORWARD CONTROL

Because the FD flow is manipulated based on fuel flow, it can be expected to change often, since fuel flow is manipulated to control either generator load or steam pressure. Changes in FD flow can cause large deviations in furnace pressure unless the ID flow is changed at the same time to keep induced and forced drafts the same. This is a requirement for stable boiler operation and an important application of feedforward control.

Depending on the boiler design and the location of instrumentation, the feedforward controller can use the sum of the primary and secondary air flow demand signals, the total air flow measurement, or the total air flow demand to establish the set point for the ID flow controller (Figure 6).

FAN CHARACTERIZATION

Because the relationship between air throughput and fan speed, vane position, or damper position will most likely be nonlinear, a characterizer should be used to obtain a linear relationship. Fan speed, vane position or damper position can be recorded at various levels of total air flow to obtain the flow characteristic of the control element. This characteristic is then inverted and implemented in a function generator to obtain the linear relationship (Figure 7).

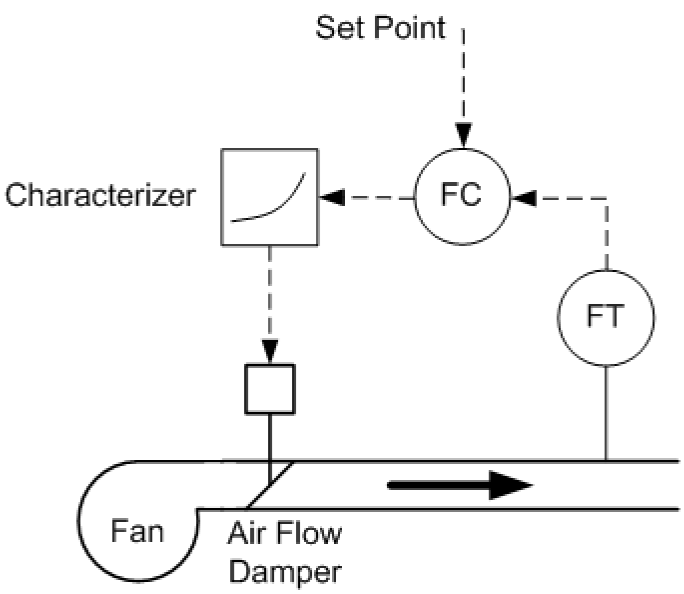

Figure 7. Characterizer for final control element linearization.

GAIN SCHEDULING

The process gain of the furnace pressure will change depending on the number of ID fans in service and in auto. To ensure fast loop response and a stable control loop in all cases, gain scheduling should be implemented on the furnace pressure controller. The controller should be tuned for minimal or no overshoot with one fan in service. The controller gain should then be divided dynamically by the number of ID fans in service or automatic control mode.

STEAM TEMPERATURE CONTROL

After separation from the boiler water in the drum, the steam is superheated to improve the thermal efficiency of the boiler-turbine unit. Modern boilers raise the steam temperature to around 1000°F (538°C) [6], which approaches the creep (slow deformation) point of the steel making up the superheater tubing. Steam temperatures above this level, even for brief periods of time, can shorten the usable life of the boiler. Keeping steam temperature constant is also important for minimizing thermal stresses on the boiler and turbine.

Steam temperature is one of the most challenging control loops in a boiler because it is highly nonlinear and has a long dead time and time lag. Adding to the challenge, steam temperature is affected by boiler load, rate of change of boiler load, air flow rate, the combination of burners in service, and the amount of soot on the boiler tubes.

Steam temperature is normally controlled by spraying water into the steam between the first and second-stage superheater to cool it down. Water injection is done in a device called an attemperator or desuperheater. The spray water comes from either an intermediate stage of the boiler feedwater pump (for reheater spray) or from the pump discharge (for superheater spray). Other methods of steam temperature control include flue gas recirculation, flue gas bypass, and tilting the angle at which the burners fire into the furnace. This discussion will focus on steam temperature control through attemperation. The designs discussed here will apply to the reheater and superheater, but only the superheater will be mentioned for simplicity.

BASIC FEEDBACK CONTROL

The simplest method for controlling steam temperature is by measuring the steam temperature at the point it exits the boiler, and changing the spray water valve position to correct deviations from the steam temperature set point (Figure 8). This control loop should be tuned for the fastest possible response without overshoot, but even then the loop will respond relatively slowly due to the long dead time and time lag of the superheater.

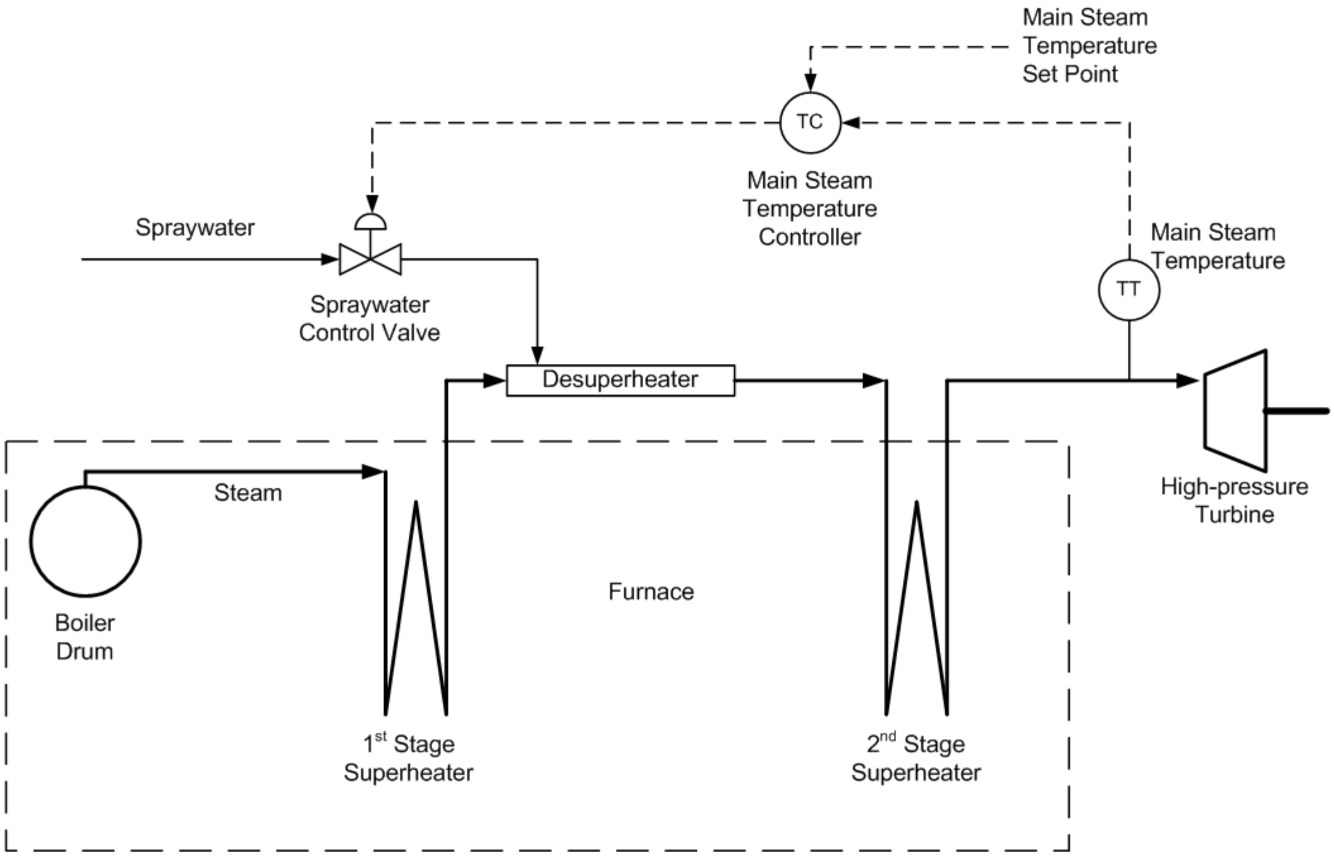

Figure 8. Simple steam temperature control.

CASCADED STEAM TEMPERATURE CONTROL

Because of the slow response of the main steam temperature control loop, improved disturbance rejection can be achieved by implementing a secondary (inner) control loop at the desuperheater. This loop measures the desuperheater outlet temperature and manipulates the control valve position to match the desuperheater outlet temperature to its set point coming from the main steam temperature controller (Figure 9).

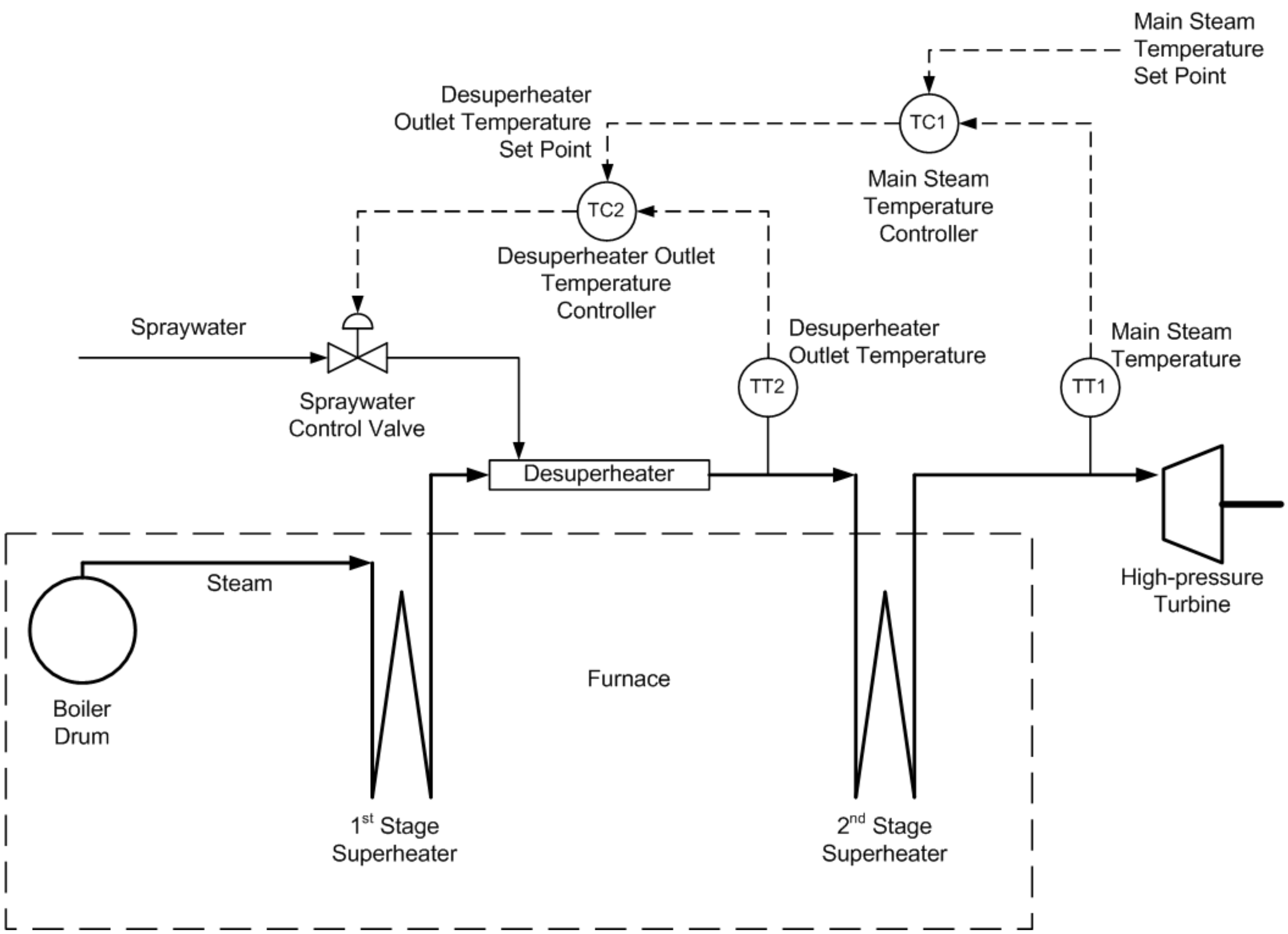

Figure 9. Cascaded steam temperature control.

Because the spray water comes from upstream of the feedwater control valves, changes in feedwater control valve position will cause changes in spray water pressure, and therefore disturb the spray water flow rate. The desuperheater outlet temperature control loop will provide a gradual recovery when this happens. If the spray water flow rate to the attemperator is measured, a flow control loop can be implemented as a tertiary inner loop to provide very fast disturbance rejection. However, in many cases spray water flow rate is not measured at the individual attemperators and this flow loop cannot be implemented.

GAIN SCHEDULING

The process dead time of the superheater increases with a decrease in boiler load because of the slower rate of steam flow at lower loads. This will have a negative impact on the stability of the main steam temperature control loop unless gain scheduling is implemented. Step tests need to be done at low, medium, and high boiler loads, and optimal controller settings calculated at each load level. A gain scheduler should be implemented to adjust the controller settings according to unit load. Because of the changing dead time and lag of the superheater, the integral and derivative times must be scheduled in addition to the controller gain.

The gain of the desuperheater outlet temperature loop will be affected greatly by steam flow rate. Changes in steam flow rate will affect the amount of cooling obtained from a given spray water flow rate. Less cooling will occur at high steam flow rates. In addition, at high loads the pressure differential between the feedwater pump discharge and steam pressure will be lower, reducing the spray flow rate for a given spray valve position (assuming the absence of a flow control loop on the desuperheater spray flow). To compensate for these nonlinear behavior, controller gain scheduling should be implemented on the desuperheater outlet temperature loop too. Similar to the main steam temperature control loop, step tests must be done at low, medium, and high boiler loads to design the gain scheduler.

DEAD TIME COMPENSATION

Because of the long dead time in the superheater, a Smith Predictor can be used to compensate for the dead time and allow much more responsive controller tuning without the risk of instability [7]. The design of the Smith Predictor must take changes in dead time, time lag, and process gain into account and it must allow these parameters in its model to be updated dynamically based on steam flow rate.

FEEDFORWARD CONTROL

During boiler load ramps in turbine-following mode, the firing rate is changed first, followed by a change in steam flow rate a while later. With the increase in steam flow rate lagging behind fuel flow rate, the additional heat in the furnace can lead to large deviations in steam temperature. To compensate for this, a feedforward from the boiler master to the steam temperature controller can be implemented.

The feedforward can use the rate of change in fuel flow or one of several other derived measurements [8] to bias the steam temperature controller’s output. In essence, when boiler load is increasing, the spray water flow rate will be increased to counter the excess heat being transferred to the steam, and vice versa. The feedforward can be calibrated by measuring the extent of steam temperature deviation during load ramps.

GENERATOR LOAD AND THROTTLE PRESSURE CONTROL

The highest-level control objectives for a power plant (also called front-end controls) are controlling the generator load (megawatts produced) and throttle pressure (main steam pressure).

BOILER-FOLLOWING MODE

It is intuitive to use the turbine governor valves for controlling generator load, and fuel flow rate for controlling steam pressure. This is called boiler-following mode, i.e. the turbine controls the load and the boiler has to follow with its pressure controls.

The boiler-following arrangement results in the throttle pressure loop being an integrating loop. The generator load controller will keep steam flow constant regardless of pressure while any mismatch between fuel input and steam flow will result in the throttle pressure ramping up or down continuously. As said before, integrating loops are difficult to tune, and long integral times must be used to ensure stability, which then reduces the disturbance-rejection capability of the loop.

Although boiler-following mode results in fast and precise generator load control, large deviations in throttle pressure can occur during load ramps. This is because the generator load controller draws steam from the boiler to meet its load demand with no regard for steam pressure or lags in the boiler.

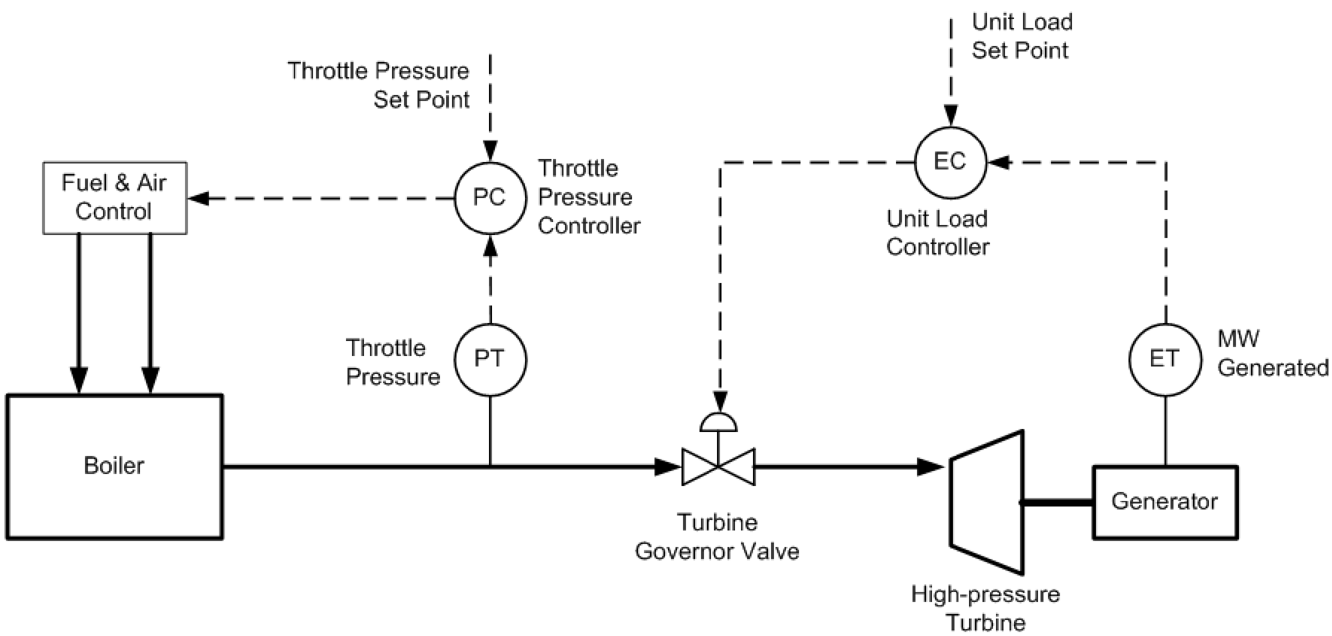

Figure 10. Boiler-following mode.

IMPROVEMENT WITH FEEDFORWARD

Due to the slow response of the pressure feedback control loop and the known, measurable disturbance acting on it (steam flow), pressure deviations can be reduced by using a feedforward from steam flow rate or first stage turbine pressure. This becomes the main driver for boiler fuel flow set point, while the throttle pressure controller simply trims the fuel flow to make up for deviations from its set point.

If the generator load controller is in manual control mode, the feedforward provides positive feedback that can quickly cause boiler instability. The feedforward needs to be disabled when the generator load controller is in manual control, or one of several other feedforward strategies can be employed [5], [10].

In addition to the pure feedforward, the derivative of first-stage pressure or steam flow rate can be added to the firing rate to obtain overfire and underfire during load ramps [5]. The derivative feedforward will add additional fuel during upward ramps and withdraw additional fuel during downward ramps, which compensate for lags in the boiler response.

TURBINE-FOLLOWING MODE

The alternative to boiler-following mode is turbine-following mode in which the boiler firing rate is manipulated to control generator load, and the governor valves are manipulated to control boiler pressure. This results in very stable throttle pressure control, but imprecise and slow-responding generator load control [11].

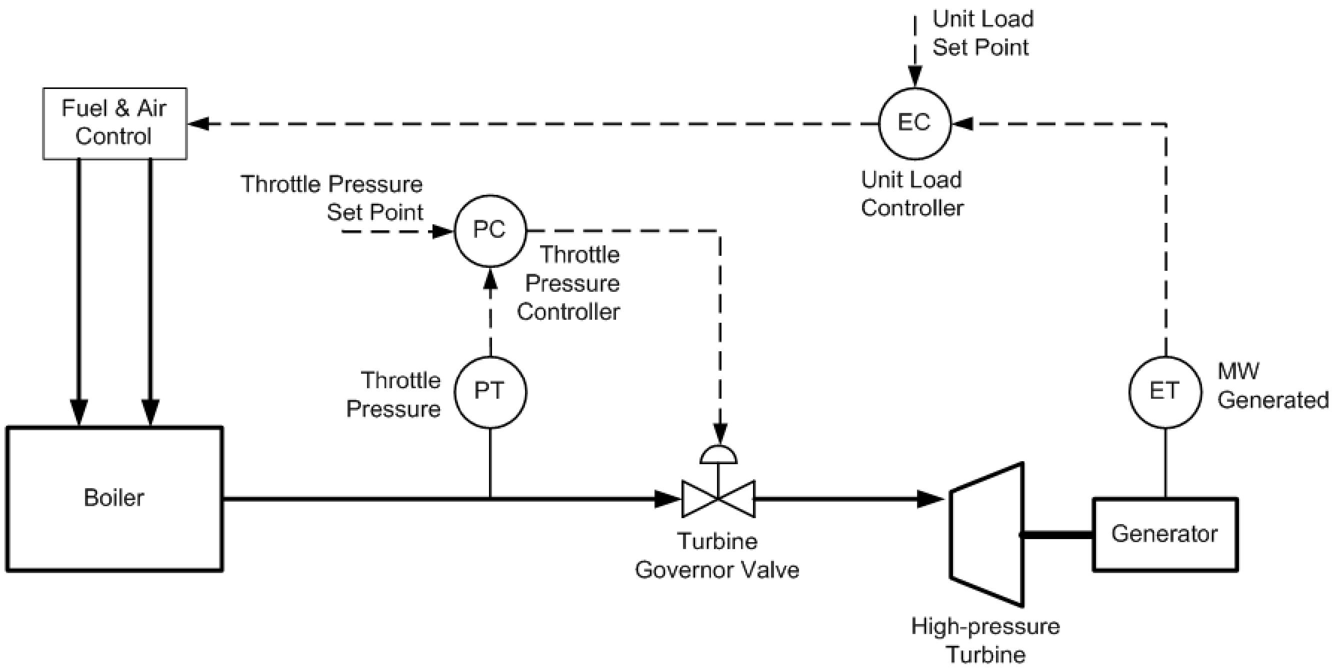

Figure 11. Turbine-following mode.

COORDINATED MODE

A very good alternative to boiler-following and turbine-following modes is coordinated control mode. In this mode the turbine valves and firing rate are manipulated in unison to regulate throttle pressure and generator load. It achieves the responsiveness of boiler-following mode but with the stability of turbine-following mode [11].

Many different designs exist, of which some are very complex [5], [10], [11]. However, the essence of the designs is that both boiler and turbine load set points must predominantly be based on a unit load set point. The boiler and turbine must be calibrated against this load signal to produce (i.e. boiler) and consume (i.e. turbine) exactly as much energy as the load signal specifies. Additionally, due to the inherent boiler lags, a dynamic rate compensator should be implemented to provide overfire and underfire during load transients (Figure 12).

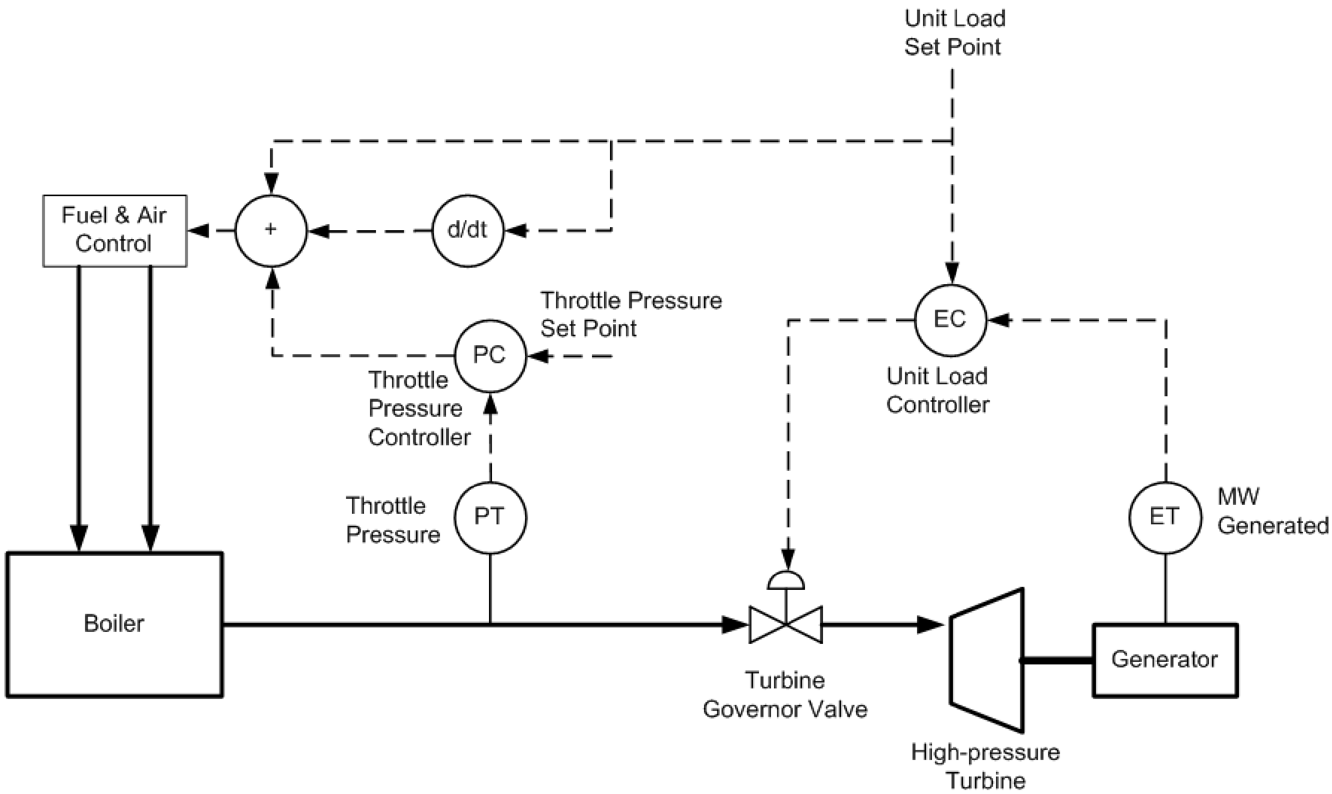

Figure 12. Boiler-turbine coordinated control mode.

SUMMARY

The stability and performance of boiler controls during transient conditions rely greatly on the application of ARC techniques. Due to long time lags, interactions, and nonlinearities present in boiler subsystems, techniques like cascade, feedforward, and ratio control, as well as gain scheduling and characterization should be applied to achieve the best possible control performance over the widest possible range of boiler loads.

Although APC holds promise of even better control performance, it has not been adopted widely in the power industry due to the difficulty justifying its cost. ARC strategies rely on building blocks already available in a modern DCS, making it a cost-effective method for improving boiler control performance.

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