Advanced Control of Steam Superheat Temperature on a Utility Boiler

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Abstract

Steam superheat temperature control is critical to the efficient operation of utility boiler steam turbines. Traditional Proportional-Integral-Derivative (PID) controllers are difficult to apply in this application due to significant time delay and changing process dynamics as a function of turbine load. This paper describes the application of a predictive adaptive model-based controller (BrainWave®) on a 430 MW Utility Boiler to control steam superheat temperature.

Keywords: adaptive control, predictive control, Laguerre orthonormal series, steam superheat temperature

1. Introduction

Steam superheat temperature control is a textbook problem for the operators of utility boilers. Steam temperature must be stable to achieve peak turbine efficiency and reduce fatigue in the turbine blades. Adjusting the amount of water that is sprayed into the steam header after the steam has passed through the super heater controls the steam temperature. The control is difficult because there is a time delay between the addition of the spray and when the steam temperature is measured. The gain, delay, and time constant of the system response also change significantly with the MW load on the steam turbine due to changes in steam flow rates. Some boilers are equipped with burner tilt and this also directly affects steam temperature when the tilt is adjusted. Typical Proportional-Integral-Derivative (PID) based control schemes require complex gain scheduling and lead-lag feed forward compensation for MW load changes and burner tilt.

This paper describes the application of a new advanced predictive-adaptive process controller that is designed to handle processes with long delay times and long time constants. The controller models the system response using a function series approximation technique called Dynamic Modeling Technology (DMT) that is based on Laguerre polynomials. This design has the unique ability to correctly model and control the unusual transient responses on the steam temperature that occur during changes in boiler load as the turbine MW load varies. Models are built for operation in each range of turbine MW load to deal with the changes in system response. The models are built automatically by the controller while operating in closed loop control. The application results demonstrate that this controller is easy to configure and can achieve a 50% reduction in steam superheat temperature variability compared to the complex PID based control scheme.

2. Advanced Controller Development

The first step in designing a model based predictive adaptive controller is to determine a method to build a mathematical representation of the process response, or model, for the system to be controlled. There are many methods to model a process transfer function response. An important practical concern is the complexity and expertise required by the user to develop such models in an industrial setting.

This adaptive controller is unique because of the technique used to model the process. Dynamic Modeling Technology (DMT) is a new method of process transfer function modeling developed at the University of British Columbia[1-6]. DMT reduces the effort required to obtain accurate process models. DMT is able to automatically build a transfer function model using a series of orthonormal Laguerre functions. The Laguerre function series is defined as:

$$l_i(t) = \sqrt{2p}\,\frac{e^{pt}}{(i-1)!}\frac{d^{i-1}}{dt^{i-1}}\left[t^{i-1}e^{-2pt}\right] \tag{1}$$

where: i = 1 to N
p = Laguerre Pole

t = time

A process transfer function can be approximated by summing each function in the series where each function is multiplied by an appropriate coefficient or weighting factor:

$$g(t) = \sum_{i=0}^{i=\infty} c_i l_i(t) \qquad (2)$$

where: $g(t)$ = Process transfer function
c = i^{th} Laguerre coefficient

The DMT modeling method is able to represent higher order process transfer functions and is inherently able to model process dead time. The user does not have to provide detailed knowledge of the process in order for an accurate transfer function to be obtained resulting in a great reduction in the effort required to model the process. An analogy would be the use of Cosine functions in the Fourier Series method to approximate periodic signals. In this case, weights for each Cosine function in the series are determined such that when the weighted Cosine functions are summed a reasonable approximation of the original signal is obtained. The weight of the Cosine functions is called the frequency spectrum of the modeled signal.

In process control, the process transfer functions are transient in nature and are not periodic so Cosine functions are not appropriate as a choice for the basis of the modeling method. The Laguerre functions used in DMT are well suited to modeling the types of transient signals found in process control because they have similar behavior to the processes being modeled. In addition, the Laguerre functions are able to efficiently model the dead time in the process response. As with Fourier series, the DMT modeling method produces a set of weights for the Laguerre functions in the series such that when the weighted functions are summed a reasonable approximation of the original transient signal is obtained. In the case of DMT, this set of weights is called the Laguerre spectrum for the signal. The DMT model is used as a basis for the design of the predictive adaptive regulatory controller using a simple d-steps ahead predictive control law.

Using DMT, the adaptive controller is able to automatically adapt to changes in gain, time constants or time delay to maintain stable control. Essentially, these process response changes result in different curve "shapes" of the transient behavior to be modeled, resulting in a new Laguerre spectrum for that process.

The effects of measured process disturbances are also modeled in order to incorporate adaptive feed forward compensation into the control strategy resulting in further performance improvements. The adaptive controller uses its mathematical models of the process to forecast process response so that set point is attained as rapidly as possible with little or no overshoot. The basic algorithm steps used in the adaptive controller are shown in Fig. 1.

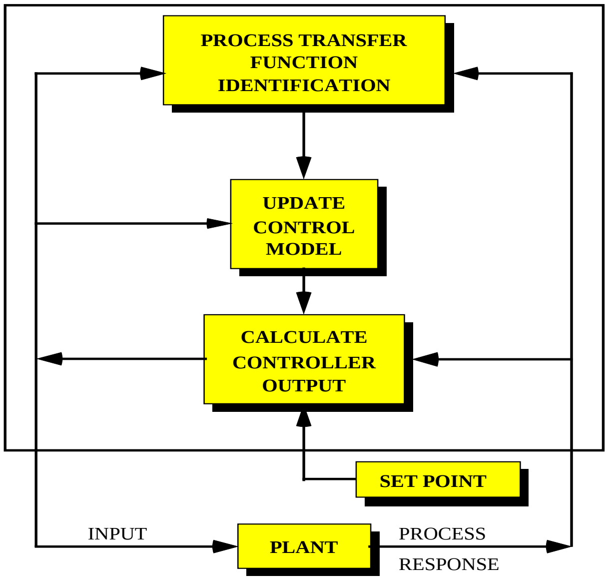


Fig. 1 - Basic Steps in the Predictive Adaptive Controller Algorithm

3. Steam Superheat Temperature Control

The steam superheat temperature is controlled by adjusting the quantity of water sprayed into the steam following the super heater. This water is supplied by the boiler feed water pumps as pressures in excess of 3,000 psi so that it can be injected into the steam header. When the steam temperature is high, the injection of water reduces the temperature and produces an increased volume of steam available to turn the turbine and produce electricity. If the steam passes through the turbine at the high temperature, no additional electricity is produced and the excess energy that was contained in the superheated steam is lost to the condenser circuit. In addition, it is not desirable to subject the turbine to excessive swings in steam temperature as it can lead to increased fatigue in the turbine blades.

Conventional Proportional-Integral-Derivative (PID) based controllers were used to control the spray vales that regulate the injection of water into the steam header. The control is difficult because there is a significant dead time between the addition of the spray water and the effect on steam temperature. This problem is compounded because the system response changes as the MW load on the turbine is changed and the boiler firing rate is adjusted to produce the required steam flow. For a change in MW load from 430 MW to 150 MW, the gain of the system increases by a factor of 3, the dead time increases from about 80 seconds to about 160 seconds, and the time constant increases from about 180 seconds to 280 seconds.

To deal with these problems, a custom gain scheduling scheme was built that would automatically load different sets of PID tuning values depending on the MW load range. Feedforward biases were also applied to the PID control scheme based on boiler gas firing rate (MW load demand) and boiler burner tilt. These feedforward signals were compensated by tuned lead/lag networks in an attempt to match the dynamic response of the PID system to changes in these variables.

The set point for the steam temperature is normally 1005°F. It is desired by this plant to maintain steam temperature within ±10°F of set point. This is normally achieved except during changes in MW load where the steam temperature will often deviate by 30 degrees or more and can take up to 2 hours to finally stabilize. An example of the PID control performance during an increase in MW load at a rate of 10MW/Minute is shown in Fig. 2. The transient in steam temperature occurs when the MW load stops ramping. In this example, the steam temperature deviated by a maximum of 16 degrees F and did not attain set point for about 23 minutes following stabilization of the MW load.

The predictive adaptive controller was installed on a PC under Windows NT. The controller is interfaced to the existing DCS using an OLE for Process Control (OPC) server. The OPC server is connected via a serial cable to a Modbus Master port on the DCS. Logic was programmed in the DCS to determine the mode for the control loops (i.e., manual, PID Auto, or Computer Auto). The predictive adaptive controller maintains a heartbeat with the DCS such that the DCS will automatically fall back to PID control in the event of a fault.

Initial estimates of the process response behavior were obtained by conducting open loop bump tests with the spray valves under manual control. This information was used by the controller to build initial DMT models for the system. The controller was placed in automatic and the models were further refined by the controller by making set point changes and by observing the effects of MW load changes and burner tilt changes on steam temperature.

The most notable model was that of the transient effect that MW load changes have on steam temperature. The controller identified this unusual transient behavior as the MW load was increased and decreased while in automatic control. When the MW load is increased, the steam temperature will initially increase but will later decrease substantially before stabilizing. This is likely due to the action of other control loops on the boiler, such as boiler feed water flow, adjusting to the new steady state load conditions. The identified DMT model and its corresponding Laguerre spectrum (weights depicted as bars) for a step change in MW load is shown in Fig. 3.

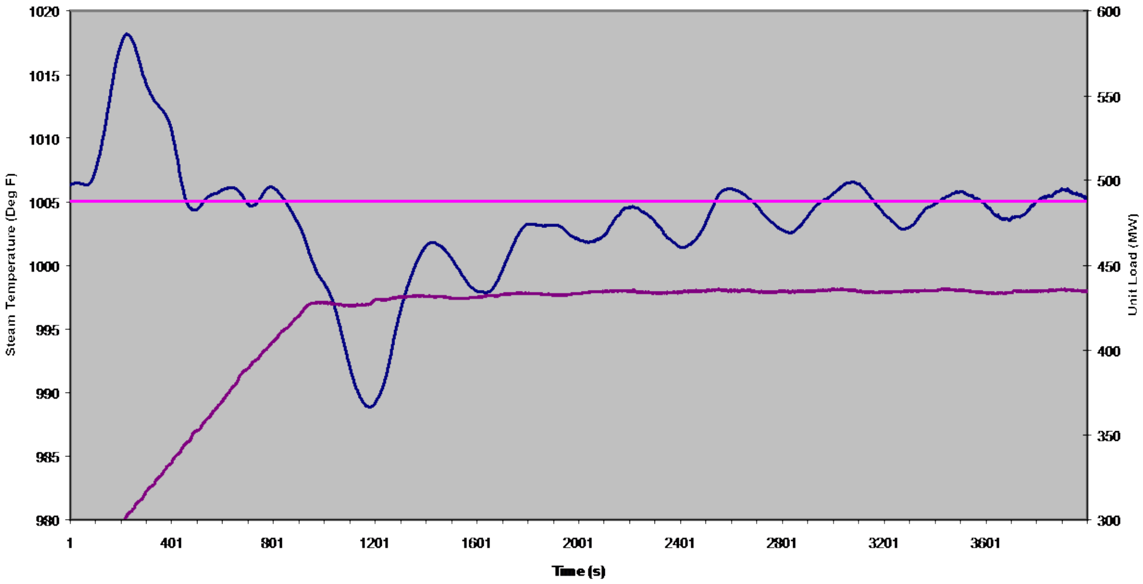
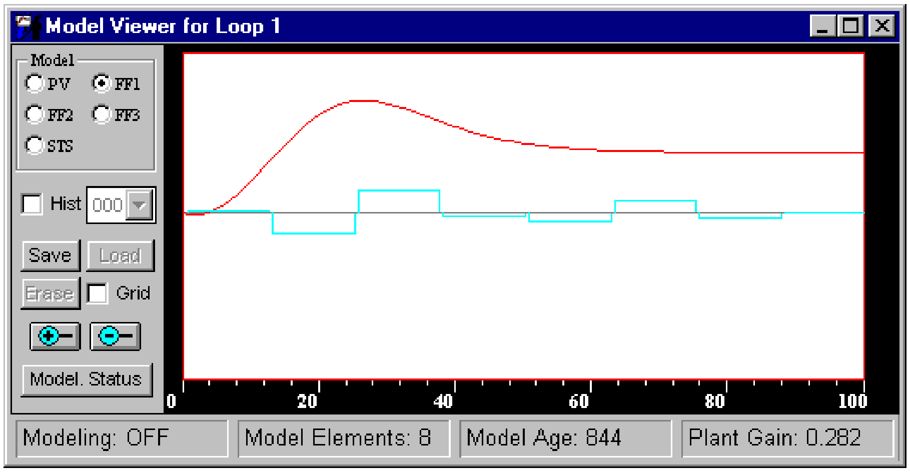


Fig. 2 - PID Control of Steam Superheat Temperature During MW Load Change



Modeling: OFF
Model Elements: 8
Model Age: 844
Plant Gain: 0.282

Fig. 3 - DMT Model for MW Load Change Effect on Steam Temperature

The plot is based on a per unit change in MW load at data sample point 0. The identified response curve represents steam temperature behavior as a function of data sample points, with a data-sampling period of 10 seconds. The dead time component of the response is clearly identified to be about 60 seconds. This example illustrates the benefits of the unstructured DMT model approach, as the user did not have to know the unusual nature of the response nor specify a particular model structure to successfully obtain a model of the system.

Correct identification of the MW load change transient response is critical to achieving good control of the system, particularly when MW changes are the most troublesome situation for the steam temperature controller. This model enables the predictive adaptive controller to anticipate the future changes in steam temperature following a load change and adjust the spray water to minimize the temperature transient. By comparison, implementing an effective lead/lag/delay scheme with PID control would be much more difficult.

The predictive adaptive controller has demonstrated a performance improvement of about 50% compared to the PID based strategy. Deviations from set point are typically within 10 to 15°F during MW load changes with the predictive adaptive controller compared to 20 to 30°F for PID. An example of the steam temperature control performance for the predictive adaptive controller during MW load changes at a rate of 5 MW/minute are shown in Fig. 4. Note that the temperature deviation is only about 5°F in this case due to the lower rate of MW load change.

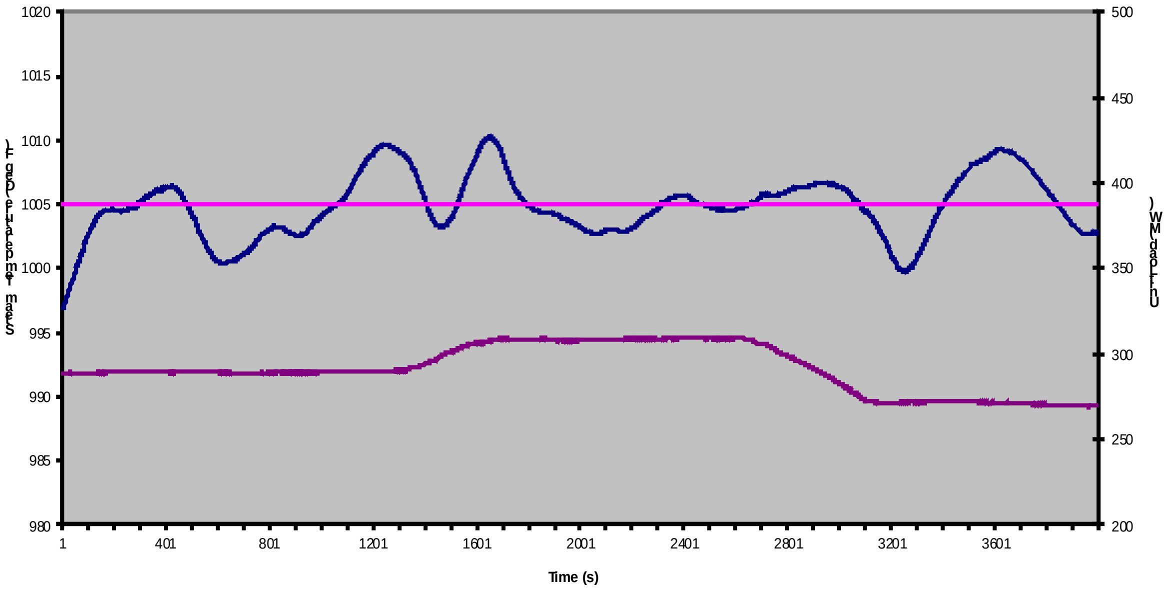


Figure 4. DMT Control of Steam Superheat Temperature During MW Load Change

4. Conclusions

The unique ability of the Dynamic Modeling Technology controller to learn the process and feed forward variable behavior automatically and continuously ensures optimum performance at all times. The problems of long development time, long setup time, repeated tuning and poor reliability associated with other advanced controllers such as Smith Predictor and other model-based controller designs are solved with this method. The DMT modeling method was found to be particularly useful for the identification of the unusual transient response of steam temperature during MW load changes. This capability was an important factor for implementing the predictive controller and achieving good control performance. Steam temperature deviations were reduced by about 50% during MW load changes compared to the existing PID based control strategy.

The DMT control approach is a new tool available to the process control engineer to implement the continuous improvement concepts advocated by Deming [7] and Juran [8] in their Total Quality philosophies.

5. References

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