Improved Load Following of a Boiler with Advanced Process Control

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Load following in power generation is a recent opportunity as time of day pricing and co-generation are adopted in refining, chemical, and power plants. Also, traditional sources of power generation are increasingly mixed with a growing fraction of emerging energy sources such as wind and solar. Wind and solar have the characteristic of being intermittently available in the case of cloud cover or as weather patterns move through an area. As of July 2011, 89% of base-load power generation in the U.S. came from coal, gas, oil, and nuclear plants (EIA, 2011). As non-traditional sources of energy integrate into the base-load, there is an opportunity to improve load-following to allow full utilization of the intermittent sources on a smart grid. The contribution of this study is to investigate the application of advanced process control for improved load following in traditional power generation, and in this case, boiler constraint control. Also, a new trajectory formulation is introduced for controlled variables in Nonlinear Model Predictive Control (NMPC). This new formulation allows rejection of process noise within a dead band while only introducing linear contributions to the objective function.

Base plant process control is typically deemed important from a safety and quality viewpoint. While these are two vitally important factors, many times, there are other aspects that greatly affect the success of a process unit. Controls are often developed from a working knowledge of a process or preconceived limitations. Although they have been very successful in the last 40 years since they were introduced, in many instances they "lack a systematic stability analysis and controller design" (Feng, 2006). It is based on operator knowledge, and adaptive algorithms (Hagan, Demuth, De Jesus, 2002). While operating a system in this manner may allow a process to proceed safely and meet quotas or quality assurance, there may be ways in which other elements of a process can be optimized (i.e. emissions, economics, and process unit life). Coal fired furnaces and boilers are an example of this. They are constrained by certain physical limits, such as rate of temperature change on tubes, allowing only restricted power cycling. Furthermore, energy from renewable resources has become increasingly popular. The National Renewable Energy Laboratory indicates that the US Department of Energy has a vision wherein wind energy contributions to total electricity production in the future is projected to increase. It is their aim that over the next 2 decades, wind will comprise 20% of US electricity production (Thresher Robinson, and Veers, 2008). However, coal-fired power plant cycling to accommodate renewable resources can actually increase wear and tear costs on coal-fired boilers. The longer the boilers sit idle, the greater the damage done to the boiler as it is ramped up after the idle time. This will decrease plant life and increase costs (Lew, Brinkman, Lefton, Piwko, 2011). It may seem as though these two factors cannot be optimized simultaneously. However, by using a robust controller, it may be possible to optimize multiple facets of a process and comply with multiple constraints.

In this study, we investigate the use of model-based control and PID controls in a coal fired furnace. By generating a differential algebraic model (DAE) of a coal-fired boiler, the constraints and parameters are explicitly modeled and controlled. Responses to process disturbances requiring power cycling are also optimized to increase profitability and process unit life..

The first step was to generate a model that could represent the cycling time and temperature changes of a coal-fired furnace. The model was created using first principles based on material and energy balances. The energy balance was built around the boiler, with appropriate heat-transfer terms for exchange between the bed, tubes, and high temperature water. A heat transfer term was incorporated into the model to represent the time delay of heating up and cooling down. The heat transfer was based on irradiative heating, as this is the dominant form of heating certain types of coal-fired boilers (Basu, Kefa, Jestin, 2000). The use of a lag variable allowed for the approximation of apparent dead time that is observed in a coal furnace. Dead time is often derived using step tests (Schnelle, Laungphairojana, Debelak, 2006). However, we used observations from operators and individuals knowledgeable about these systems. Load cycles were then simulated with control of the system through the APMonitor software. Control of the system was accomplished using trajectory tracking and constraints in Nonlinear Model Predictive Control (NMPC). For comparison the use of a PID controller on this system was explored. The results of the two control simulations were then compared.

NMPC was able to predict appropriate controller outputs in order to achieve the correct ramping rate and cycling. The model-based control was superior for several reasons. The physical constraints of the system may be set and the controller keeps the system explicitly within those bounds. For example, typical practice for changing furnace load is to increase heating output at a rate of about 1%/min. This rate constraint can be controlled explicitly in the multivariable controller along with trajectory load following. NMPC uses predictive values based on current measurements in order to achieve the set point within the dictated constraints. It was demonstrated over the entire range of operation, including transient and steady state conditions. It optimized load changes and achieved set points within the reliability constraints.

One of the major benefits of the PID is its simplicity. In simulations, it was able to achieve and maintain set point and reject disturbances. However, the controller had several shortcomings. In order to achieve the desired output temperature, the controller frequently saturated. The PID also had several challenges with start-up and ramping cycles. Typically, load changes are performed at a slower rate. The PID controller was unable to accommodate these constraints. In certain instances, especially those in which large disturbances were introduced, the PID controller violated the constraints on temperature gradient for the boiler temperature tube integrity. This situation can greatly affect safety, performance, and economic success, especially over the lifetime of the furnace. The PID controller was however very useful at steady state or for small disturbances. It was able to keep a set point, but not effective enough to be used in cases where large disturbances were encountered. It was not as robust as would be desirable in certain circumstances, especially those in which large disturbances or changing conditions are frequently observed.

Process data for this study was obtained from an operating coal-fired boiler facility. With current controls on the boiler, load changes can be performed at about 1%/min. A model-based controller challenges this restriction by driving to actual process constraints. Load changes can be performed faster if the constraints are better understood, or perhaps, in order to prolong boiler life, they should be done slower. The model-based approach enables an environment where constraints can be explicitly targeted in moving the boiler to the new power generation load. As a final statement, there are also some concerns that certain process units may be too complex to be accurately modeled. In these cases it may be beneficial to use a combination of empirical and first principles methods to obtain the best results. Future extensions to this work may also include forecasting of energy availability and load, time-of-day pricing, and anticipated peak power demands. This will enable feedforward information for improved load following optimization.

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