Requirements for Successfully Implementing and Sustaining Advanced Control Applications

Authors

Jacques F. Smuts [1], Aaron Hussey [2]

[1] OptiControls Inc, League City, Texas
[2] Electric Power Research Institute (EPRI), Charlotte, North Carolina

Keywords

Advanced Control Applications, Sequential Automation, Control Loop Performance Monitoring and Tuning, Advanced Process Control

Abstract

The power generation industry has been slow in adopting certain advanced control applications like sequential automation, control loop performance monitoring and tuning, and advanced process control. Economic justification for advanced control projects has been reported as being the main barrier to entry, while a perception that these technologies are not yet proven in the power industry, and the requirement for highly skilled personnel, also restricts adoption. This paper presents the results of a survey that was conducted to identify the barriers to implementing advanced control applications, and the requirements for implementing and sustaining these applications. End users in the power industry were surveyed through an online tool and detailed experiences were gathered through telephone interviews and a broad literature review. Results of the survey, interviews, and literature review are documented in this paper, and recommendations are made for successfully implementing and sustaining advanced control applications in the power industry.

Introduction

It has been observed that the power industry is not taking advantage of new and advanced control technologies as much as other large industries like refining, chemical and oil & gas. The Electric Power Research Institute (EPRI) has launched a research project to determine why the power industry is not adopting these technologies as rapidly as others, and to provide justification and guidelines for implementing such technologies. The research was focused specifically on three fields of advanced control:

- Sequential automation systems (i.e. the automation of startup and shutdown sequences)

- Control loop performance monitoring (CLPM) and tuning software
- Advanced process control (APC) systems, including model predictive control (MPC), neural network control and expert system control.

The three fields will collectively be referred to as Advanced Control Applications (ACA) in this paper.
The research comprised:

- An Internet-based survey to test the level at which power producers have implemented the three areas of ACA and what they found as barriers to implementation.
- Phone interviews with power companies on their experiences with implementing ACA.
- Interviews with technology vendors to obtain their perspective on challenges with- and requirements for implementing ACA.
- A survey of published case studies on the implementation of ACA.

Adoption of Advanced Process Control in Large Industries

ARC Advisory Group has published two reports [1, 2] on the sales volumes of distributed control systems (DCS) and real-time process optimization and training (RPO) systems, respectively. The two reports break down the sales of DCS and RPO by industrial sector. The results from the two ARC studies show that within the four largest industrial markets (power, refining, chemical and oil & gas) the power industry is spending the most on DCS upgrades and replacements, while it spends the least on APC systems. The two studies combined confirm that the power industry is lagging behind the other major industries on adoption of APC.

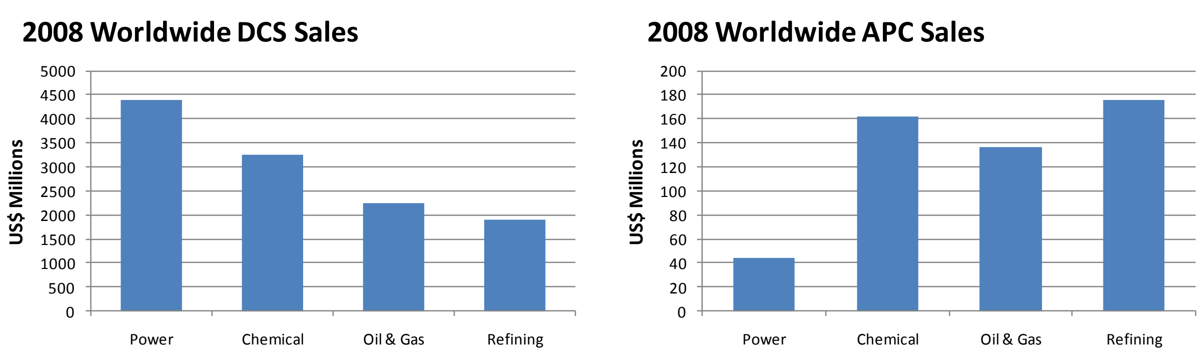

Figure 1. Relative to DCS sales, the power industry lags behind other major industries in adopting APC.

Survey on Adoption of ACA in the Power Industry

A web-based survey was conducted to test the level at which power producers have implemented the three components of ACA. A link to the survey was emailed to EPRI's "I&C Interest List" with 667 contacts. 67 responses were received of which 60 were from the United States and 7 from outside the United States.

The survey results, and especially those in Table 1 below, are not believed to be representative of level of interest the power industry as a whole has in ACA. The survey was voluntary and was titled "EPRI Poll on Advanced Control Technologies." Therefore, it is expected that invitees with no interest in advanced control would probably not have responded. The survey would be more representative of sites that have a significant interest in ACA.

Key results from the survey are presented in Tables 1, 2 and 3 below. Table 1 indicates that power producers find it reasonably easy to get sequential automation implemented (success-to-fail ratio of 2.7:1), but difficult to get APC implemented (success-to-fail ratio of 0.45:1). Controller Tuning and Assessment has a success-to-fail ratio of about 1:1.

	Sequential Automation	**Loop Assessment & Tuning**	**APC**
Successfully implemented	40% (27)	37% (25)	15% (10)
Could not implement	15% (10)	35% (24)	32% (22)
Planning to implement	9% (6)	9% (6)	12% (8)

Table 1. Survey results on implementing the three ACA subgroups. Numbers in parentheses indicate the number of participants who checked the option, percentages indicate numbers as a percentage of all 67 participants.

Table 2 shows the barriers to ACA implementation, and it indicates that the major barrier is economic justification. This topic will be discussed in detail later.

	Responses
Not economically justified	37% (25)
No budget for advanced control projects	25% (17)
Sufficiently proven technology does not exist	16% (11)
Shortage of adequately skilled personnel	21% (14)

Table 2. Barriers to implementing ACA.

Table 3 shows the correlation between ACA groups and barriers to implementation. The table indicates that average sequential automation project has fewer barriers to implementation compared to loop assessment and tuning software and APC.

It is interesting that the main barrier to implementing sequential automation seems to be a shortage of skills. This is likely because sequential automation projects are relatively easy to cost-justify (compared to loop assessment and tuning software, and APC), making its implementation the biggest hurdle. As expected, technology is not a significant barrier for sequential automation projects because most DCS come with sequential automation features already built in.

Skills and cost justification were reported as the two main barriers for implementing loop assessment and tuning software, but proven technology was also seen as a significant barrier. Economic justification and technology are the main barriers for APC projects.

	Unable to Implement		
	Automation	Tuning / Assessment	APC
Not economically justified	32%	56%	56%
No budget for advanced control projects	24%	53%	35%
Sufficiently proven technology does not exist	9%	45%	55%
Shortage of adequately skilled personnel	36%	57%	43%

Table 3. Correlations between the three ACA types and various barriers to implementation.

Phone Interviews and Published Literature

The second phase of the research was to conduct phone interviews with survey participants who agreed to participate in the follow-up survey. Twelve interviews were conducted, each interview taking between 30 minutes and an hour. The last phase of the research was a comprehensive literature search for case studies on the implementation of sequential automation, loop assessment and tuning software, and APC. An interesting observation is that there are a substantial number of papers on APC case studies, while the other two fields of ACA had very few. The relevant findings gathered from all the research avenues were combined to make up the remainder of this report.

Sequential Automation

Most industrial plants are complex to operate and require detailed written procedures for starting up and shutting down the plant or major pieces of equipment. These procedures consist of a series of operational steps that need to be followed in sequence. Each step must be completed and a number of operating statuses such as the position of a valve or outlet temperature of a heater must be checked to meet specified criteria before the next step may be executed. A complete startup may consist of dozens of these steps.

Although sequential automation capabilities are available in the control systems of most power plants, many use the bare minimum of sequential automation, relying mostly on the operators for executing written procedures.

A Note on Combined-Cycle Plants

Interviews and literature revealed that combined-cycle plants have implemented automatic startup and shutdown sequencing to a far greater extent than other power plant types. Coal-fired power plants do not generally cycle on and off frequently. This lowers the need for incorporating an automated startup system into them. In contrast, combined-cycle plants are good targets for implementing automated startup systems due to their frequent cycling.

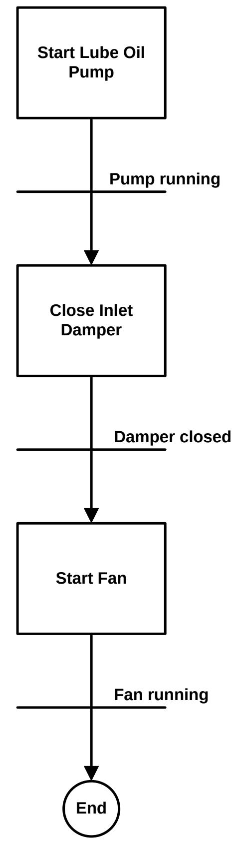

Figure 2. Sequential automation diagram.

Barriers and Challenges

Several barriers and challenges make it difficult for power plants to implement sequential automation. These are discussed below.

Novelty of Sequential Automation

Sequential automation is still a relatively unapplied technology for the power industry (especially in the United Sates). Very little design guidance exists in print and the benefits of automation systems are not well documented in the industry.

DCS Capabilities and Tools

More than one plant reported limited capabilities of the sequential automation functions built into the DCS and the associated design tools. Unlike add-on software like APC, there is little incentive for DCS providers to improve the capabilities of these tools.

Quality of Operating Procedures

It is possible that operating procedures could be outdated or lack sufficient detail to be used as a basis for the design of the sequential automation.

Changing of Operating Procedures

If the plant is used to changing operating procedures frequently, the automation of such procedures will make it significantly more difficult to change procedures.

Availability and Reliability of Field Instrumentation

Field instrumentation originally designed purely for indication purposes might be of inferior quality, making them unsuitable for use as inputs to a sequential automation system. Also, instrumentation might have fallen into disrepair through a lack of maintenance or years of operation in hostile environments. Often, new instrumentation has to be added and hand-valves have to be automated for the full implementation of sequential automation.

Increased Cost and Effort of Maintenance

Plants that have implemented automation on a large scale reported that they now need more manpower to maintain the instrumentation that has become essential to the operation of the plant.

Vendor Promotion

Sequential automation is already available in the DCS, and except for selling low-margin services, there is no incentive for DCS vendors to promote the implementation of sequential automation.

Requirements for Success

A sequential automation system is in many ways similar to any automation system. However, certain aspects of sequential automation projects are unique. These aspects and other requirements for the long-term success of sequential automation systems are discussed below.

Resource Commitments for Duration of Project

The design effort of automating the start-up of a combined-cycle HRSG takes about one year, while its implementation can take three to four months. Management has to commit to providing the right resources to the sequential automation project. Competing projects should not rob the automation project of its resources and the design and implementation must be a near-fulltime activity to be efficient. It is also important to keep the same personnel throughout the project. Replacing personnel mid-project will impose a significant learning curve on new personnel and will likely introduce inefficiencies to the entire team.

On-site Champion

Because the plant can be operated without sequential automation, it is easy to give up on automation should technical or other challenges arise. It is therefore very important to have a resourceful and motivated person on site to be the project champion. The champion can carry the project through difficult times and ensure its success.

Design Team

The design should be done by a team, not a single individual. The design team should consist at minimum of an engineer intimately familiar with the process being automated, an experienced plant operator, and a consultant or DCS engineer with detailed knowledge of the sequential automation capabilities of the DCS. If possible, the team should be led by a multi-disciplinary engineer familiar with the process and the DCS's capabilities, and have prior experience in sequential automation. If the automation system has to interface with other processes and control systems, subject matter experts of those systems should be part of the initial planning and brought in to consult to the design team at relevant times throughout the design.

Design & Testing Tools

The design engineers should be trained in the capabilities of the sequential automation design tools of the DCS, and work within this environment as much as possible. It is also useful to test the sequential logic in a simulator for catching bugs and design errors.

Design Basis

Existing operating procedures should be used as the basis for the design. If the procedure is incomplete, it should be updated to reflect all actions taken by an experienced operator while executing the actual task on the real plant. The design should also make provisions for differences in plant conditions, for example cold-start, warm-start, and hot-start could each have a different operating procedure. Additional sequences must be implemented to achieve shutdown [5]. The design should also provide for "lead-lag" preferences on redundant pieces of equipment. Lee [6] provides a wealth of information on designing sequential automation.

Pre-work

Some field instrumentation will have to be replaced or at least repaired. In some cases hand-valves have to be automated for the full implementation of sequential automation. It is also worth noting that single-pushbutton startup is not possible without stable regulatory controls, especially drum level controls [5]. Control loop problems have to be addressed before commissioning the sequential automation.

Implementation Team

Depending on site staffing skills and availability, consideration should be given to contract the DCS vendor or an experienced third-party to do the actual implementation.

Commissioning

Plant management might be pushing hard to get the plant back on line after an automation project. This may prevent project personnel from fixing bugs in the automation sequences. If the project team normally resides on site, this can be done when the next opportunity arises, but if the project team goes off site, these issues may never be resolved. It is therefore important to get all the problems fixed during the initial commissioning so that a fault-free and useful automation system can be handed over to operations.

Maintenance of Instrumentation

Time, personnel, and financial resources must be made available for the upkeep of the system. Similar to feedback controls, sequential automation relies heavily on feedback from field instrumentation. Instruments providing equipment status feedback to sequential logic programs should be maintained on a schedule to ensure they work when required.

Changes to Operating Procedures
Although the sequential logic itself does not require routine maintenance, operating procedures do change and these changes then need to be made to the sequences too.

Operator Training
An undesired side-effect of automating operator procedures is that operators may forget how to do the automated tasks manually. New operators may never learn how a plant startup sequence is really done. It may be prudent to have operators periodically do plant startups manually, using the automation system as a guide, to ensure they understand all the steps involved and will be able to do it manually if it ever becomes necessary.

Control Loop Performance Monitoring and Tuning Software

The performance of a power plant is highly dependent on the performance of its control loops [11]. A key requirement for good control loop performance is proper tuning of the controllers. Although tuning can be done manually, commercially available software tools have greatly simplified the tuning process. Software tools have also been developed for the assessment of control loop performance and flagging of control loops that need attention. This section of the report deals with these two types of software tools.

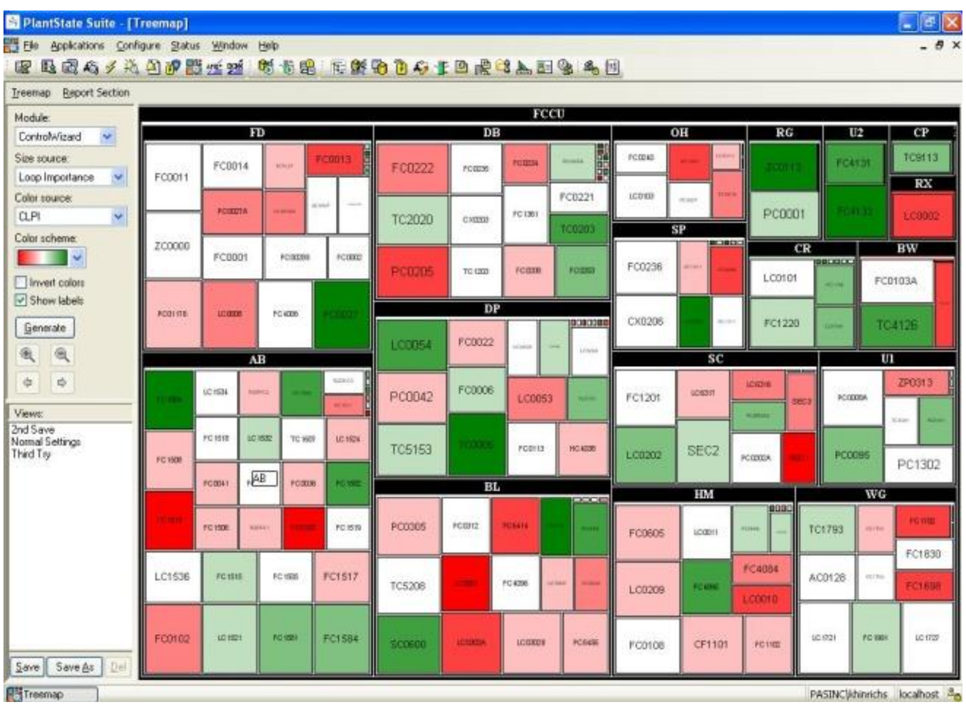

Figure 3. Loop performance assessment software indicating good performance in green and poor performance in red.

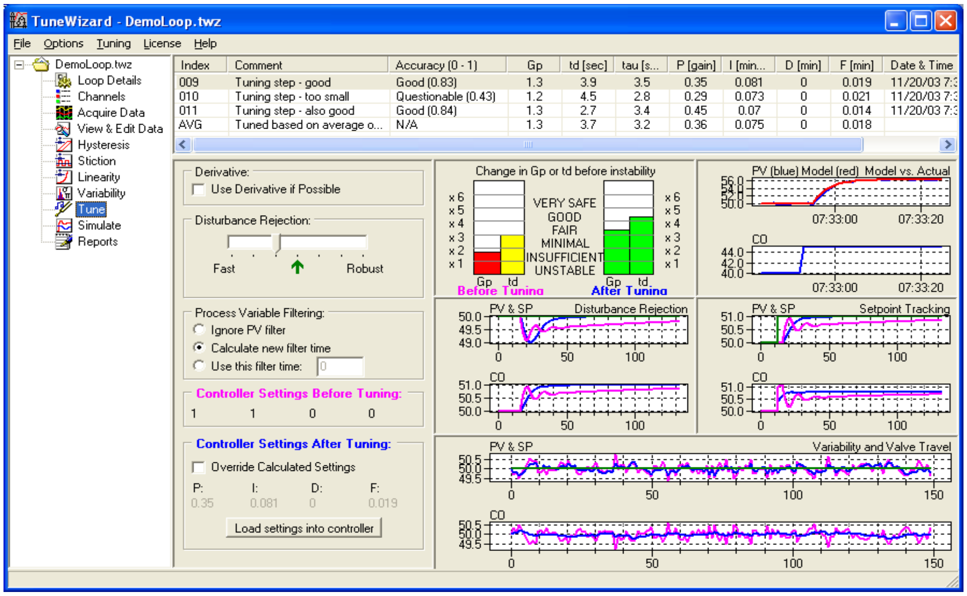

Figure 4. Loop tuning software with various simulations.

Barriers and Challenges

Many barriers to implementing CLPM and tuning software exist, driving down the adoption rate of these systems. A brief discussion of these barriers follows.

Competing with Human Skills

Plants often have a few “old hands” on staff that have been tuning loops for many years and do a fine job without the need for any tuning software. It is likely that the *old hands* will be set in their ways and reluctant to use new technology to do the same job.

Missing Essential Features

Power plant controls make extensive use of cascade and feedforward controls and most tuning tools do not lend themselves very well to tuning these control strategies [8]. Many CLPM and tuning software tools do not natively support these features making them less useful to the power industry.

Advanced Skill-Set Requirements

Controller tuning software is very technical in nature and addresses a technically challenging problem. But apart from the technical complexity, tuning software is in essence just a tool, and like any tool it requires a skilled person to operate it. Unskilled users, who don’t understand the basics of process control and controller tuning, will very likely fail when trying to use tuning software.

Difficulty in Cost Justification

Although some tuning tools are available at a reasonable price ($5,000 and below), loop performance assessment software costs several tens of thousands of dollars. Most companies would require a solid cost justification to authorize spending this kind of money. No case studies could be found on how controller tuning actually improved the bottom line of a power plant.

Step Testing Required

Tuning tools require at least one, but preferably several process step tests in which a controller's output is given a step change by the operator [10]. Operators are not in favor of doing step tests on processes because of the upsets they cause. Inexperienced operators may be completely unwilling to do step tests.

Bad Experience with Software

Some first-time users of tuning software try it on the most difficult loop at their site. These loops most often have problems not related to tuning, like control valve stiction or process nonlinearities. The users then give up on the software when it cannot properly tune the loop, and declare the software a failure.

Network Security Issues

Nuclear facilities have very strict requirements for connecting software to the control system networks. This could make data collection from controllers at a nuclear plant so tedious that engineers simply do the tuning using trial-and-error methods, and look at the process trend displays for an indication of loop performance.

Competing Interests

Unless a loop performs so poorly that it upsets production, improving control performance is often considered optional – even if it is economically beneficial. Because it is optional, it will almost always lose out to mandatory tasks.

Requirements for Success

Data Acquisition

Process data for loop analysis should be non-compressed and collected at a rate fast enough to capture the loop dynamics. Data is best obtained through OPC (object linking and embedding for process control). Careful consideration should be given to the rate at which loop performance assessment software acquires data from the OPC server.

Application Tuning

After installation, controller performance assessment software does not know the exact function or objective of any particular control loop in the process. The software uses many default settings against which it compares actual loop performance. As a result, it might flag poor loop performance on a loop that is behaving perfectly normally. Configuration parameters and thresholds for loop performance assessment and diagnosis must be adjusted in the software to improve the accuracy of loop performance assessment. This "tuning" of the system can take a few days.

Verification of Software Results

Recommended tuning settings that are far different from those in the controller should be verified. If the controller was not tuned properly to begin with, the new settings could be correct, but verification and engineering judgment should be used. In any event, more than one step test should be used during the tuning process, and tuning calculations from each step test should be compared to the others.

Training

CLPM and tuning software are specialized applications. Software training (and process control training if required) by the vendor or qualified third party is highly recommended. Software user guides can be of inferior quality, and is probably good as a reference guide only.

Advanced Process Control

Power plants (and especially coal-fired boilers) have unique process control challenges that lend themselves well to APC-type solutions. These include steam temperature control, throttle pressure control, and combustion control. These processes are multivariate in nature and simple PID controllers alone might be unable to keep the processes within limits during load transients and other boiler disturbances.

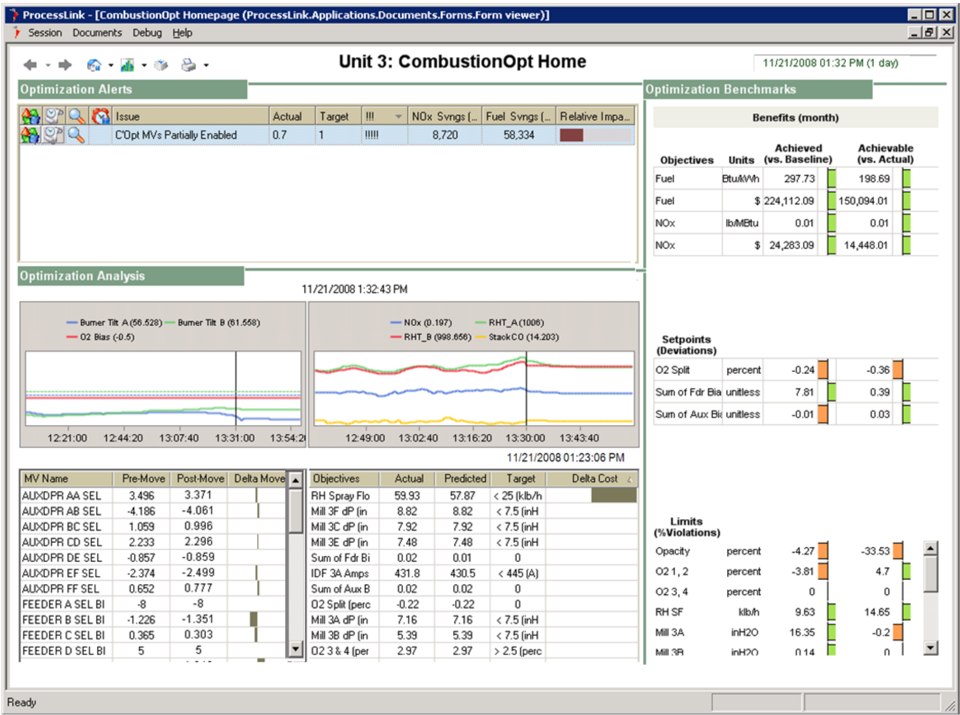

Figure 5. User interface of a combustion optimization system (Courtesy: NeuCo).

Barriers and Challenges

Although APC technology may be ideal for solving boiler plant control problems, the adoption rate among power companies has been very slow. This is attributable to several challenges the power industry faces when considering the implementation of APC.

Complexity

APC technology and the software supporting it is quite complex and the power industry does not have a wealth of experience with it. Plant engineers are unlikely to accept complex control systems that they do not understand and that they often think the vendors do not completely understand either [12].

Shortage of APC-Skilled Personnel

Power companies often would find implementation of APC very difficult, because the skill level at sites are more geared towards maintaining the DCS, instrumentation, and control valves. Sites do not normally have engineers who could implement or maintain APC applications.

Competing with Advanced Regulatory Controls (ARC)

The power industry has done much more with ARC (feedforward, cascade, and ratio control, overrides, gain scheduling, characterization, etc.) than the other large industries. Designs have evolved over time to improve control performance significantly over simple feedback control.

The incremental benefits of APC are therefore less than what it would have been without ARC. Because of the reduced incremental benefits, it is more difficult to cost-justify APC.

Uncertain Returns
Refining and petrochemical industries, where APC has proliferated, frequently cost-justify APC on two tangible benefits: increased production rate and improved product quality. In the power industry, production rate is mechanically limited (and currently there is over-capacity), and product quality doesn't apply. Therefore, APC has to provide other benefits to be of interest to the power industry.

Penalties and Rewards for Load Response Not Passed Through
Plants within a fleet normally don't get paid for fast load response, so there is no incentive for individual power plants to install APC and improve load ramp rate.

Implementation of Selective Catalytic Reduction (SCR)
During the 1990s and early 2000s, fossil power producers had a significant interest in APC for combustion control to meet NO_X regulations. As the regulations tightened and penalties increased, most boilers were equipped with SCRs to lower emissions. SCRs lowered the NO_X emissions so much that additional benefits from combustion optimization were diminished.

Increased Maintenance Cost
Field instrumentation previously used just for indication may become an essential measurement in an APC design. Similarly, position control of burner tilts and dampers become much more important when these are manipulated by the APC system. Consequently, to ensure optimal operation of the APC system, the cost of maintaining its associated field instrumentation and control elements will likely increase.

Fuel Costs Passed on to Customers
In regulated markets, where power plants don't compete on cost of production, there is no real incentive to improve heat rate. Fuel costs (and savings) are passed on to customers and not to the company's bottom line. In this environment corporate executives and plant managers should be incentivized by the company to lower the cost of production.

Requirements for Success

EPRI [17] provides a comprehensive technical overview of the design, implementation, and long-term support of an APC system. Below are a few items supplementing the information presented in the mentioned EPRI report.

Vendor Involvement

APC technology and the software supporting it is quite complex and the power industry does not have much experience with it. APC software suppliers, in contrast, have a wealth of experience with their software, and have access to in-house or third-party consultants for implementing their technology on power plants. It is advisable that the software vendor be intimately involved with the design and installation of APC systems.

Preparatory Work

Few APC systems directly drive the final control elements (valves and dampers). Most APC systems send set points or biases to regulatory feedback controls (PID control loops) [13]. It is therefore important that the regulatory control level work very well before implementing APC. APC vendors normally include a “pre-test” phase in an APC project for tuning controllers and fixing control problems before the step testing for model building is done.

Dealing with Nonlinearities

For steam temperature control, multiple linear models would be required to deal with the changes in process response between high and low loads. APC controllers support the bumpless switching of process models. Plants with three models in their steam temperature controllers reported that the performance was good throughout the load range. A test installation at one site used a single model, and it was reported to be insufficient.

Commissioning and Tuning

When the APC system has been commissioned and is running online for the first time, it will be placed in a “predict-only” mode in which predictions are made for the controlled variables and new moves are calculated for the manipulated variables, but these are not actually implemented. Some tuning will likely be required to tweak the sizes of the moves. The system will then be placed in control mode and further tuning might be necessary to optimize its performance.

Risk Reduction

APC payments can be contractually structured to be based on performance of the system as quantified savings or increases in profit. This takes the risk off the power company and ensures that the APC provider is very diligent and possibly conservative with the up-front benefits estimation. It also ensures that benefits are properly measured and quantified after completion of the project.

Training

It goes without saying that the operators need to be trained on the new APC functionality. Training is of utmost importance for operator acceptance and for them to be able to operate the new system and navigate through the new operator graphics pages. They also need to understand what the APC system is controlling, the inputs it uses and how its outputs are brought back into the regulatory controls. Depending on the technical expertise of the engineering and maintenance staff on site, they could be trained to perform various levels of maintenance activities. At minimum they should be able to debug communications problems and get the system back on line after a communications failure or computer reboot.

Maintenance

Major changes to plant equipment, like installing low-NO_X burners or changing superheater heat transfer surface area, will require a recalibration of some or all of the APC models. Capable engineering staff might also identify additional feedforward inputs that can improve the operation of the APC system. Additional process modeling will be required for this too. It is recommended to establish a maintenance contract with the APC supplier for resolving issues that lie beyond the capabilities of plant staff. Some APC vendors offer remote monitoring capabilities for this purpose.

On-site Champion

Because the plant can run without the APC turned on, operators will likely turned it off if problems arise. The system could remain off indefinitely unless the site has a champion who takes care of the system in the long run by resolving issues as they come up, and calling in the supplier to resolve larger issues when required.

Conclusion

The power generation industry has been slow in adopting certain advanced control applications like sequential automation, control loop performance assessment and tuning, and advanced process control. In the case of advanced process control systems, the power industry is investing at only one quarter the rate of other comparably large process industries.

Implementation of sequential automation is being favored by combined cycle plants because of the high rate of startups and shutdowns many of these plants are being subjected to. Justification for sequential automation projects is mostly based on minimizing startup times and reducing the chance of operator error. Project implementations are relatively straightforward since all programming is done in the existing control system. In some cases field instrumentation needs to be upgraded and hand operated valves automated. In the long term, scheduled maintenance on valves and instrumentation is essential for sustaining the system. Any changes to written operating procedures also need to be implemented in the control system.

The value of loop assessment and tuning software remains difficult to express in monetary terms. Justification for implementing assessment software hinges on its ability to identify potentially costly control problems, while tuning software can be justified on time savings and possibly on the superior loop performance it provides compared to trial-and-error tuning methods. Loop assessment and tuning software potentially make control engineers more effective by pointing out loop problems to focus on, and providing tools to help fix those problems. Training in process control and the software tools are required for success.

Early in the decade advanced process control systems were commonly justified as a low-cost method for reducing NO_X emissions through combustion optimization, while these systems normally also reduced heat rate. Unfortunately, the NO_X benefit has been diminished over the last few years by the installation of selective catalytic reduction systems. While project justification based on heat rate improvement is possible in many cases, this is not as attractive as environmental compliance used to be, especially in regulated markets. To build a stronger case, cost justifications for advanced process control should be based on a combination of benefits, including heat rate reduction, improved ramp rate, improved reliability, and possibly a reduction in NO_X or ammonia usage.

The power industry remains short on experience in advanced process control systems, and power producers should rely on the expertise of technology vendors or outside consultants to ensure the proper selection of technology, appropriate designs, and smooth implementation of these systems. Long term maintenance includes planned maintenance of all field instrumentation and final control elements used by the system, updating process models after changing mechanical or thermodynamic properties of equipment, software upgrades and server maintenance.

References

[1] *Distributed Control Systems Worldwide Outlook*, ARC Advisory Group, 2008

[2] *Real-time Process Optimization and Training Worldwide Outlook*, ARC Advisory Group, 2009

[3] *Natural Gas Navigator*, U.S. Energy Information Administration, http://www.eia.gov/dnav/ng/hist/n3020us3a.htm

[4] *Demonstration of Automation on a Combined-Cycle Plant*. EPRI, Palo Alto, CA, and Southern Company, Birmingham, AL: 2007. 1013344

[5] S. Leibbrandt, W Thackston, *Fully Automating HRSG Feedwater Pumps*, Presented at 53rd ISA POWID Symposium, 6-11 June 2010, Summerlin, Nevada

[6] D. Lee, *Plant Automation Design Methods*, Presented at 53rd ISA POWID Symposium, 6–11 June 2010, Summerlin, Nevada

[7] *Diagnostic/Troubleshooting Monitoring to Identify Damaging Cycle Chemistry or Thermal Transients in Heat Recovery Steam Generator Pressure Parts*, EPRI, Palo Alto, California, March 2005. 1008088.

[8] *Automated Boiler Control System Tuning Demonstration*. EPRI, Palo Alto, CA and Southern Company, Birmingham, AL: 2009. 1020370.

[9] *Quantifying the Value of Improved Control System Performance*, EPRI, Palo Alto, CA, and Southern Company Services, Inc., Birmingham, AL: 2004. 1009844.

[10] *Control System Tuning Assessment Guidelines*, EPRI, Palo Alto, CA: 2002. 1004425.

[11] *Tuning Guidelines for Utility Fossil Plant Process Control. Volume 2, The Technician's Guide to Tuning.* EPRI , Palo Alto, CA: 1994. TR-102052.

[12] N. W. Rees and C. X. Lu, *Some thoughts on the advanced control of electric power plants*, Transactions of the Institute of Measurement and Control 24,2 (2002) pp. 87–106

[13] L. Gordon, D. Roberts, and D. Labbe, *Optimizing Heat Rate with Model Predictive Control on Riley Turbo-Furnace Units*, Joint ISA POWID/EPRI Controls Conference, 2002

[14] *Power Plant Optimization Guidelines*, EPRI, Palo Alto, CA: 1998. TR-110718.

[15] D. Labbe, S. Coker, A. Speziale, *Entergy Independence NOx/Heat Rate Optimization and Steam Temperature Control with Neural Net/Model Predictive Control Combo*, 48th Annual ISA POWID Symposium, 2005

[16] S. Barnoski, D. Labbe, J. Graves, W. Poe, *Coal Mill and Combustion Optimization on a Once-Through, Supercritical Boiler with Multivariable Predictive Control*, Joint ISA POWID/EPRI Controls and Instrumentation Conference, 2004

[17] Application Guidelines for Advanced Control in Fossil Plants, EPRI, Palo Alto, CA: 1999. TR-114339.