

Adaptive predictive expert control of superheated steam temperature in a coal-fired power plant

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SUMMARY

This paper describes the application of an adaptive predictive expert (ADEX) control solution to the attemperation process for superheated steam temperature control in the ScottishPower coal-fired power station at Cockerzie near Edinburgh in Scotland. The project comprised two phases, the first of which was a trial to establish the feasibility and potential benefits of ADEX compared with the existing control system by using a software platform on PC connected to the plant Programmable Logic Controller (PLC) via Object linking and embedding for Process Control (OPC), and the second phase was to verify and install a permanent, robust solution using an ADEX controller module with a digital link to the plant PLC. The overall objective of the project was to reduce steam temperature variations caused by load changes and other perturbations in order to protect the steam turbine (Unit 3) and to minimize thermal stresses in the attemperation pipework and boiler and so minimize premature failures along with associated cost risk. In the first phase, ADEX demonstrated a 50% improvement in reducing steam temperature variation overall compared with the existing method, and the subsequent installation of the ADEX controller module provided the necessary robustness and backups for a final industrial solution. The results of both phases are displayed graphically. Copyright © 2012 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Improving the operating performance of large scale, coal-fired power stations through the application of advanced control techniques offers a compelling means of obtaining substantial economic benefit. In particular, a key opportunity for improvement is the control of superheated steam temperature; an issue which has been the subject of considerable research over many years with a view to improving the performance of the control dynamic and integrity of plant equipment. These objectives translate into an increase in maximum turbine efficiency and protection against premature damage which can be caused through large variations in steam temperature with respect to design values [1].

The attemperation process for steam temperature control is characterized by having nonlinearities, time variable dynamics, sudden perturbations, and variable time delays. For this reason, efficient control of superheater steam temperature had remained a problem for many years. The variable time dynamics have two principal causes. The first is that varying the load produces significant dynamic changes in the plant. The second is because of the existence of unpredictable events such as deposition of dirt in the heat exchangers which directly affects the coefficients of heat transfer.

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The economic benefits deriving from efficient control of superheated steam temperature are recognized [2] and affect principally the function of the turbine. Basically, these benefits come down to two concepts.

The first is associated with the temperature of inlet steam. This benefit is proportional. The higher the temperature, the greater the benefit in turbine efficiency. Nevertheless, there is an upper limit to this temperature set by permissible operating conditions. If the steam temperature exceeds this value, the turbine will be damaged. There is also a lower limit because of the danger of water condensing out and damaging the turbine.

The second benefit results from the reduction in temperature fluctuations, which cause thermal stresses leading to mechanical failure through cracks in turbine blades and in steam pipework. A reduction in fluctuations will result in longer useful life and reduced maintenance costs [3].

Other studies in the application of advanced control, predictive control, and /or adaptive control to the regulation of superheater steam temperatures in large power plants are presented in [1, 4–9] and [10] as well as a previous implementation of adaptive predictive control (APC) at the Pasajes de San Juan power station [11], belonging to the company Iberdrola.

In this paper, an industrial application of adaptive predictive expert (ADEX) control [12, 13] in the coal-fired power plant at Cockenzie is presented. Cockenzie is situated in Prestonpans, 8 miles to the east of Edinburgh in Scotland. The plant has a total potential of 1200 MW based on four units of 300 MW each. The plant has been in operation since 1967.

The objective was to install a control and optimization system in Unit 3 to improve the performance of superheated steam temperature control, particularly during periods of load change in order to

- Improve the control precision of superheated steam temperature entering the turbine.
- Stabilize steam temperature during load changes.
- Maximize turbine efficiency.
- Minimize thermal stresses which can damage the attemperation pipework and the boiler.
- Demonstrate and prove the functionality of the ADEX controller module.

The project was carried out in two phases. Phase I was carried out on Unit 1 at Cockenzie in order to establish the viability and efficiency of ADEX methodology for this application. An independent assessment of the results found a 50% reduction in steam temperature variation using the ADEX control methodology compared with the existing PID control system for the attemperation process. A decision was subsequently made by ScottishPower to proceed to Phase II; a permanent solution that satisfied all operating requirements including redundancy, equipment integrity and efficiency.

In Phase II, the control and optimization system comprised an ADEX control hardware module [12, 14] called 'ADEX controller module' (ADEX CM), together with a control strategy implemented in a Rockwell CompactLogix L32E to manage the attemperation system.

The project maximized the use of existing equipment such as PLCs to ensure minimum intrusion and cost. Additions included extra programs to the existing PLC and new monitoring graphics using the existing iFix SCADA system. Because of the age of the plant, the principal objective of improving control precision was to reduce thermal stresses in the pipework and boiler rather than increase turbine efficiency.

In this paper, Section 2 provides a brief description of the attemperation process, Section 3 outlines the control challenges, Section 4 explains the background to ADEX methodology, and Section 5 provides details of the ADEX controller module architecture. Section 6 presents the ADEX control strategy used for the attemperation process and the ADEX controllers' configuration. The results obtained in Phase I are presented in a comparative manner in Section 7. Section 8 describes the work scope required for Phase II, illustrating the extent to which existing equipment was used and presents the experimental results obtained using the ADEX control module. The conclusions are presented in Section 9.

2. PROCESS DESCRIPTION

The attemperation system diagram is shown in Figure 1. Water from the 'heaters and feed pumps' is supplied both to the economiser and to the rest of the boiler via feed regulation valves, and in

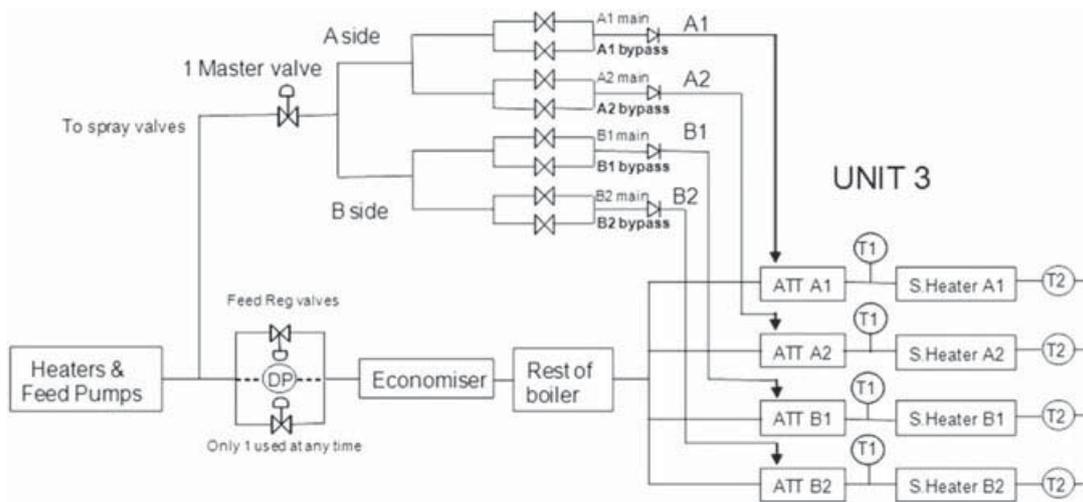


Figure 1. Attenuation process diagram.

addition, to the pipe supplying all four attenuation units. The flow rate of water passed to the economizer circuit and to the rest of the boiler to obtain the final superheated steam is controlled using the feed regulation valves.

The steam output from the drum, (inside the block labeled as 'rest of boiler'), is split over four superheater circuits as shown in Figure 1. Each of these circuits comprises an initial superheating stage, followed by an attenuation process, followed by a second and final superheating stage. The steam flow emerging from all of these lines is merged into a common pipe before finally entering the high pressure steam turbine.

The flow rate of water sent to the common pipe of the attenuation system is controlled by means of a master valve after which the water splits into two paths labeled A and B, corresponding to each side of the boiler and which are further divided into A1 and A2 for side A and B1 and B2 for side B.

The master valve remains fully open most of the time during operations. There is an attenuation unit for each of the four lines A1, A2, B1, and B2. Each of these lines has two valves, the upper one shown in Figure 1 called the 'main valve' and the lower one called 'by-pass valve'. These valves control the flow rate of spray water injected into the superheated steam in order to maintain the temperature at the set point. At no time during the operation are both lines, main and by-pass, functioning simultaneously (i.e., never a mixture), and for most of the time, the by-pass lines are used because the valves are more precise for fine control purposes. The means of controlling temperature T2 is through controlling T1 using the attenuators.

It should be noted that the load control system in Cockenzie is of the type 'boiler follows turbine', where the load demand requirement acts directly on the turbine control valve in order to obtain the desired power generated by rapidly changing the flow rate of steam to the turbine. The boiler control system is left the task of controlling steam pressure and other variables such as steam temperature as well as perturbations induced by the turbine control system which directly affect steam pressure. This control strategy produces rapid responses to the control of generated power, but this speed also results in large variations in steam pressure over a wide range of load changes with all that implies for plant reliability [5].

3. CONTROL CHALLENGES

The superheated steam temperature presents one of the most difficult control challenges faced by coal-fired power plant, particularly in the presence of real time variations in the dynamics of the attenuation process because of load changes during normal running, and start up, and shutdown of

the unit. The parameter which most affects steam temperature is the boiler pressure, which inversely affects temperature, that is, when the pressure decreases, the temperature increases and vice versa.

The main factors which affect the control of the steam temperature are as follows:

- (1) Firstly, boiler pressure variations because of the following:
 - Variations in load (demand) which affect the steam flow rate to the turbine and this in turn affects the steam pressure and so with temperature.
 - Inherent delays between load change and consequential change in coal flow. Note that the units can operate in frequency response mode for long periods.
 - Several different types of coal with different calorific values may be used by the plant; this introduces a further disturbance to boiler pressure.
 - The burners are selected, because the top burners affect temperature, whereas the bottom burners affect pressure.
- (2) Secondly, the attemperator water spray flow rate depends on the differential pressure across the feed regulating valves (see Figure 1).
- (3) Thirdly, as a result of the nature of the boiler construction, there are differences in the amount of heat transferred in each of the superheaters in the four lines.
- (4) Fourthly, there are time delays of between 20 and 30 s between the attemperator spray action (T1) and the final steam temperature entering the turbine (T2). These time delays are variable because of load and boiler pressure variation.
- (5) Finally, precise control of temperature T2 (minimizing the variation) entering the turbine often requires large and abrupt variations in attemperation temperature to compensate, especially during load and pressure changes. As one of the main objectives is minimizing thermal stresses in the pipework, and too much variation in T1 actually aggravates the problem in the attemperation pipework, a compromise needs to be reached between T2 temperature precision and stabilizing temperature T1.

All of these interactions and constraints are difficult to deal with in a conventional control environment.

4. ADEX METHODOLOGY AND IMPLEMENTATION

4.1. Methodology concepts

Adaptive predictive expert control methodology is characterized by combining the following three features: (i) anticipating the process evolution using a model of the process to apply predictive control; (ii) adjusting the model parameters in real time using an adaptive mechanism in such a way that the prediction error converges towards zero; and (iii) incorporating the available process knowledge into the controller operation.

Thus, ADEX methodology integrates APC [14] and expert control [15] in order to provide a control solution able to apply expert control when convenient and APC when appropriate, thereby optimizing the global process operation. ADEX combines APC with expert control by defining domains of operation for each of them in an integrated setup. The evolution of process variables determines if APC or expert control should be applied to the process according to the corresponding domain of operation [16].

The AP domains are those in which the dynamic cause-effect relationship between the input and output process variables can be identified in real time by means of a time-varying model driven by an adaptive mechanism. In these domains, APC can be applied, and the process operation is thus optimized.

Adaptive predictive expert enables the application of expert control in certain domains of operation where manual control can provide a more robust and efficient control than APC. Operator experience is used to develop the rules imitating manual control intelligence that will drive the process output from the expert domain towards the AP domains.

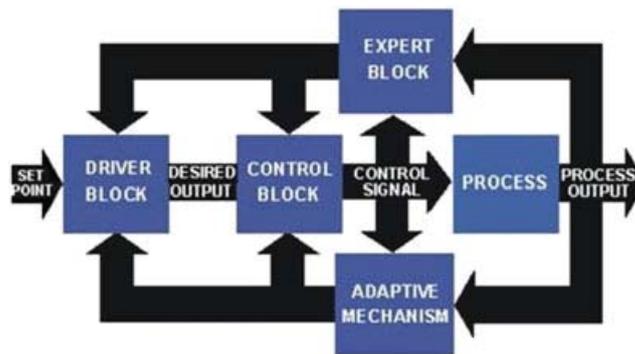


Figure 2. Block diagram of an adaptive predictive expert controller.

4.2. Block diagram and implementation

Figure 2 presents the block diagram of an ADEX controller. From the input/output (I/O) process variable information, the expert block on the top of the figure identifies the process domain of operation and determines whether APC or expert control will be applied to the process.

When APC is applied to the process, the control block in Figure 2 becomes a predictive model that generates the control action to make the predicted process output equal to the desired output, which is generated by the driver block. At the same time, the adaptive mechanism adjusts the predictive model parameters from the prediction errors in such a way that makes them tend towards zero.

When expert control is applied to the process, the control block becomes an expert system that generates the control action emulating the process knowledge of an expert human operator by means of rules.

The optimization of industrial process performance by means of ADEX controllers usually requires the integration of these controllers within control and optimization strategies (COS) to be applied to the process. A full description of ADEX controllers and a software platform, designed for the development and application of COS integrating these controllers is presented in [12]. This platform named ADEX Control & Optimization Platform (COP) normally runs on a PC and operates in parallel with the local control system, acquiring the I/O variable data required for the COS execution via OPC and sending back the computed optimized control signals in the same way. The version of ADEX COP platform used in Phase I of this project is described in [16]. The next section describes the ADEX control module used in Phase II of the project which replaced the ADEX COP platform.

5. ADEX CONTROLLER MODULE

The ADEX CM has been developed to bring ADEX technology closer to PLC control level and offer a more robust industrial solution.

The ADEX CM robust solution requires the COS to be written on the PLC control program that includes ADEX controller graphical operators, but the corresponding code to execute these controllers is installed inside the ADEX CM, which essentially is a fully protected enclosed coprocessor with digital links to the PLC. The controllers in the ADEX CM can be executed therefore by the program in the PLC as determined by the corresponding ADEX controller operators.

The ADEX CM, in addition to containing the coprocessor that executes the ADEX controllers, also contains functions necessary for power, communications with the PLC that are via RS-232 or RS-485 and support to a USB link for configuration purposes as shown in Figures 3, 4, and 5.

Figure 5 shows both the working and setup configuration of the ADEX CM. To the right of the figure, the working configuration shows that the ADEX CM is connected only to the PLC which is connected both to the plant (actuators and sensors) and to the SCADA system which displays variables graphically.

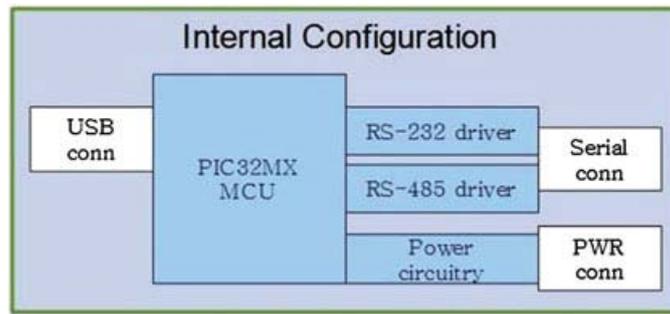


Figure 3. Block diagram showing internal configuration of ADEX CM.



Figure 4. Photograph showing ADEX CM in plant.

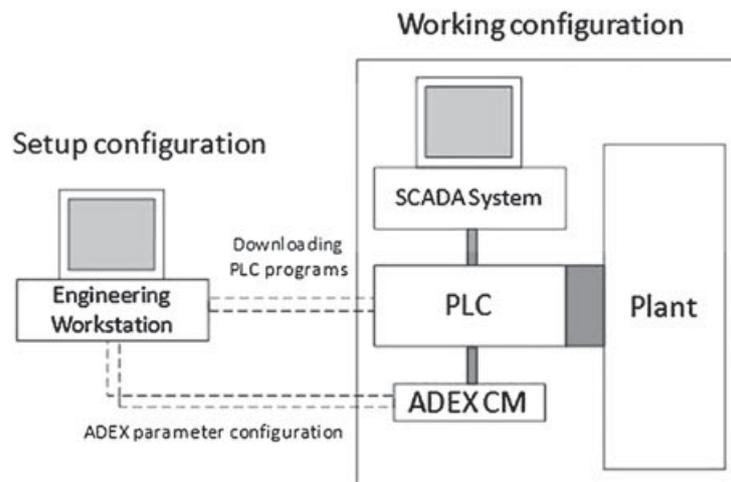


Figure 5. Diagram showing the set up and working configurations for the ADEX CM.

At the outset, or whenever required, an engineering workstation can be connected in order for an engineer to configure the ADEX CM parameters, or program the PLC control logic to include the COS. In the case of Cockenzie, the PLC and SCADA system were already part of plant operation so the addition of ADEX involved using all the same equipment and indeed PLC functions, with the only addition of the ADEX CM.

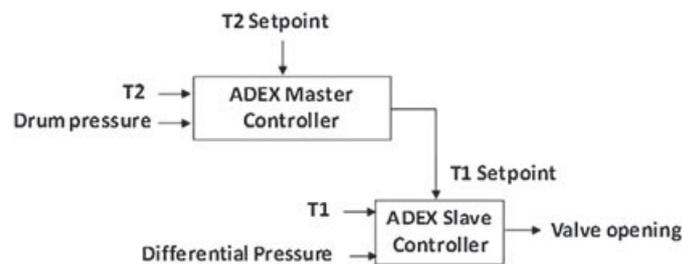


Figure 6. ADEX control strategy.

6. CONTROL STRATEGY AND ADEX CONTROLLERS

6.1. Control strategy

The ADEX control and optimization strategy used for the attemperation lines in both phases of the project was basically the same and is shown in Figure 6. This strategy comprises a master-slave cascade with two 2x1 controllers. The master controller measures the temperature T2 (the temperature of superheated steam entering the steam turbine) and attempts to keep this temperature as close as possible to the T2 setpoint by adjusting the set point value for temperature T1 (the temperature of superheated steam exiting the attemperation unit) to the slave controller. This will be referred to as the 'T2–T1 process'. The slave controller measures the temperature T1 and regulates the spray water flow rate by adjusting the spray water valve (the 'T1-valve process').

This strategy involves the control of temperature T1 between the superheaters to minimize thermal stresses which can damage the attemperation pipework while maintaining tight T2 temperature control. The strategy separates the dynamic relationship between temperature T2 and the spray water valve opening into two subprocesses; the T2–T1 process and the T1-valve process, which offers the advantage of identifying two simple transfer functions. The master controller identifies the dynamic relationship between temperature T1 and temperature T2, whereas the slave controller identifies the dynamic relationship between temperature T1 and the spray water valve opening. This last controller, in its identification process, is taking into account the nonlinearities in the spray water valve.

The master controller uses drum pressure as a perturbation variable, because this variable has a great effect on steam temperature as explained in Section 5. Also, the slave controller uses the differential pressure across the feed regulating valves as a perturbation variable because it affects the final flow rate of spray water applied for attemperation.

6.2. ADEX controllers configuration

Both the ADEX COP platform and the ADEX CM provide the tools to configure the Expert (EX) and AP domains included in a controller [12, 16]. For AP domains, this is achieved by setting the value of the so called structure variables that determine the operation of the controller in the corresponding domain. The most important structure variables are those that define the AP model structure, the control period, the limits on the control variables, the noise level on the process output, the maximum slope of the desired output trajectory, and the prediction horizon.

The master controller, used in the previously discussed ADEX control strategy, had three AP domains. One of them was centered on the T2 temperature set point, and its upper and lower limit values were respectively equal to $\pm 5^\circ\text{C}$ on each side of the set point value. An upper AP domain used the upper limit of the middle domain as lower limit and the lower AP domain used the lower limit of the middle domain as an upper value. If the T2 temperature is out of the upper AP domain or lower AP domain, the expert control stops the adaption with the objective of protecting the AP model.

This AP domain structure was set in order to add robustness to the ADEX master controller. For example, when temperature T2 exceeded the upper limit of the middle AP domain, driven

by unknown disturbances that could adversely affect the identification of the process dynamics in the AP model, the change to a different domain resulted in the re-initialization of the AP model parameters to a default set of values corresponding to the new operating conditions. This set was conveniently chosen from previous operation of the controller in the new domain. Each time the T2 temperature changed from one domain to another, the AP model parameters were re-initialized. The slave controller had the same I/O structure as the master controller but included only one AP domain of operation.

The AP models used by both controllers computed, at each control instant k , the a priori estimation of the incremental process output, $\hat{y}(k|k-1)$, by means of a general equation of the form

$$\hat{y}(k|k-1) = \sum_{i=1}^f \hat{a}_i(k-1) y(k-i) + \sum_{i=1}^g \hat{b}_i(k-1) u(k-i) + \sum_{i=1}^h \hat{c}_i(k-1) w(k-i) \quad (1)$$

where $y(k)$, $u(k)$, and $w(k)$ are increments of the measured process output, process input, and the disturbance variable, respectively, and the AP model parameters, and represent the identified process dynamics at time $k-1$. The estimation error, $y(k) - \hat{y}(k|k-1)$, drives the AP model parameters adaptation at time k using gradient parameters algorithms that guarantee the convergence of the estimated error towards zero.

The AP model defined in (1) can also be used to predict the process output trajectory in a prediction horizon, in which a performance criterion that takes into account the desired process output trajectory determines the control action generated by the controller.

The parameters f , g , and h that determine the structure of the AP model were chosen equal to 2, 3, and 2, respectively for both master and slave controllers.

The master controller

- Sends a control action with a frequency of 50 s (control period),
- Lower limit of control action is equal to the steam condensation temperature plus 20°C,
- Made little consideration of noise on the measured process output,
- Had a maximum slope for the desired output trajectory equal to 4°C per control period, and
- Had a prediction horizon equal to five control periods.

The slave controller had

- Control period of 10 s,
- Range of attemperation valve opening varied between 0 and 100%,
- Noise practically not considered on the process output,
- A maximum slope for the desired output trajectory equal to 6°C, and
- Had a chosen prediction horizon also of five control periods (50 s).

7. PHASE I: IMPLEMENTATION AND RESULTS

Phase I was a temporary installation of ADEX to prove the concept, so the existing PID controllers were left intact. This allowed a direct comparison between ADEX and PID control. The performance of the attemperation process of line A1 under ADEX control was compared with that of line B1 under PID control, and similarly, the performance of line A2 (ADEX) was compared with the performance of line B2 (PID). The attemperation results for both sides of the boiler were measured simultaneously using the PI system of ScottishPower.

Adaptive predictive expert was implemented by loading the ADEX COP platform onto a PC supplied by ScottishPower linked via OPC to a PLC which was linked in turn to the various valves and sensors used by the system. The PLC was effectively used to bring all the signals together so that they could be available to the ADEX system. A switch was also provided in the plant control room enabling control to be passed from the existing PID control system to ADEX and vice versa. In order to make the transfers 'bumpless' when going from ADEX to the local control system, the latest attemperation bypass valve position was passed to the local control system by the operator manually.

The results of the Phase I study are presented as follows:

Figure 7 shows the trend curves of T2, T1, load, and valve position during a 2¹/₄-h period. The scales for T2 and T1 are represented on the left axis of the graph, whereas the load scale is represented at the right. This figure presents an early result that shows the start of ADEX control before much work had been carried out on the configuration of the ADEX controllers demonstrating an immediate improvement in T2 control with an accompanying smoothing of the load profile. As can be seen, this precision was achieved by adjusting T1 considerably, using the attemperation process.

After this initial trial, several adjustments were made to improve the ADEX performance, particularly during load changes. These changes were made over a period of 10 days, and the overall results, recorded in the PI system, were examined independently at the behest of ScottishPower. These results are shown in the Figures 8 and 9.

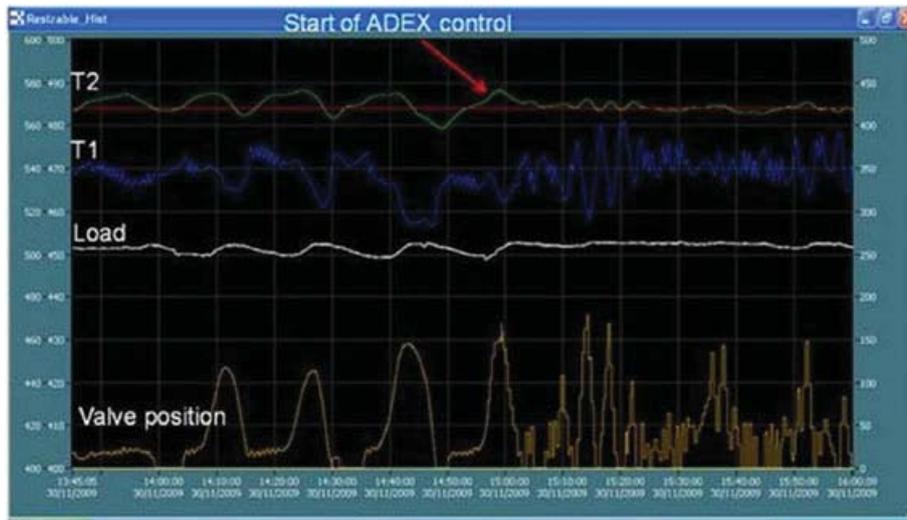


Figure 7. Change over from PID to ADEX control at the start of the tests.

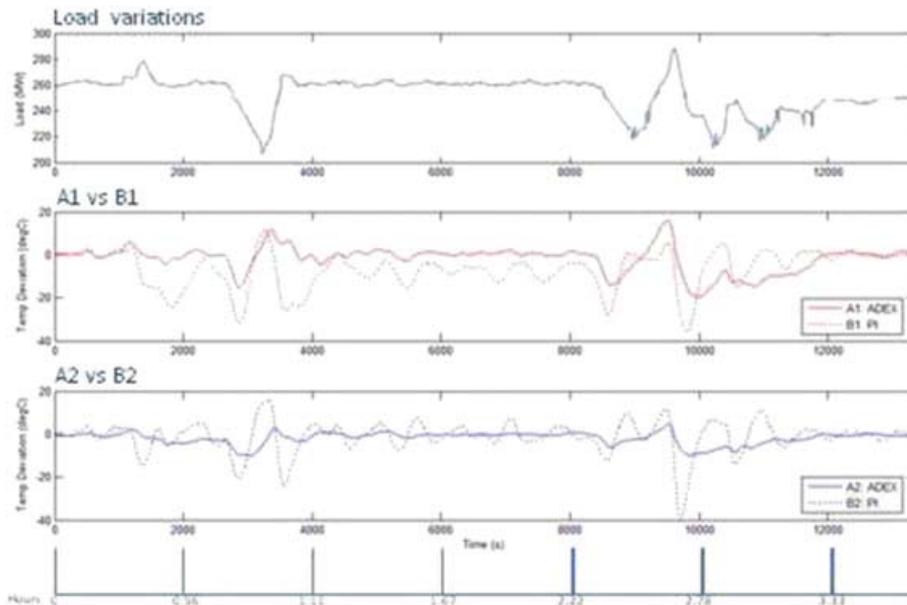


Figure 8. Comparison between ADEX and PID performance over a 3¹/₂-h period.

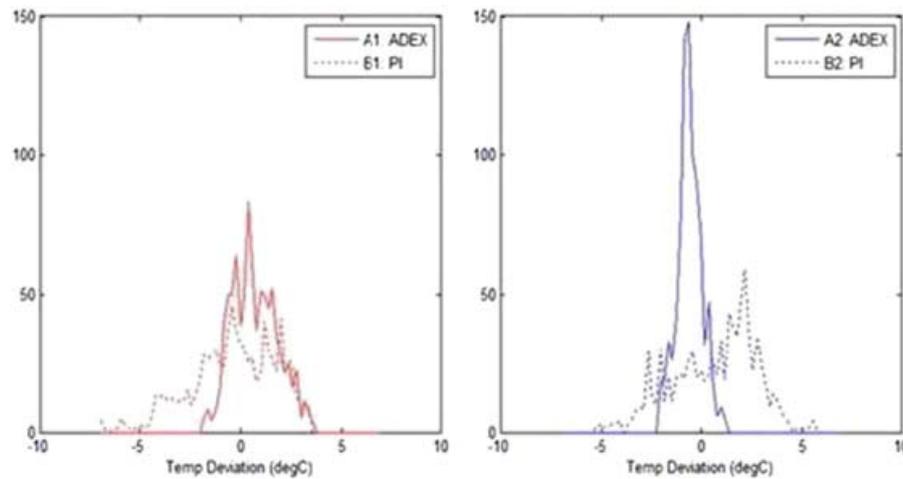


Figure 9. Histograms showing overall ADEX and PID control schematics performance.

Figure 8 shows comparative results over a $3\frac{1}{2}$ -h period during which two perturbations in the load took place (one after about 45 min and the second around $2\frac{1}{2}$ h). Overall, the solid line in each case represents ADEX performance, whereas the dotted lines represent that of PID. Figure 9 provides a frequency histogram of results which gives a better overview of performance with the A2 versus B2 comparison showing a more marked improvement.

Overall, the improvements obtained from the ADEX application after only 10 days of test and adjustments were sufficient to demonstrate a convincing benefit. An independent analysis of the overall results reported an improvement of more than 50% in temperature excursions for both steady state and during load changes. The 50% improvement, shown particularly on the left-hand graph in Figure 9, was limited by the fact that the spray valves were at their low limits. However, the graph on the right-hand side of Figure 9 shows that where the control action is not constrained, the improvement increased to 80%.

As a consequence, the decision was made to proceed with Phase II and a permanent installation of ADEX for attemperation control at the Cockenzie plant.

8. PHASE II: IMPLEMENTATION AND RESULTS

This section describes the work scope which was required to install ADEX permanently on site with a robust solution. The objective of this work was to provide a permanent solution which involved avoiding any disruption of the production process, maximizing the use of the existing equipment as far as possible, and providing adequate backup in the event of any breakdown in the link between ADEX CM and the PLC.

As was shown in Figure 1, there are two lines in each of the four attemperation lines with valves in each referred to as 'main' or 'bypass', with the bypass line valves being controlled by ADEX. It was decided first of all to retain the previous control system on the main valves as an independent standby system. At the same time, the wiring for the bypass lines was removed and a PLC was added to enable the connection of ADEX to the bypass valves. Only one PLC was needed to link all ADEX functions to the plant. The ADEX control strategy was programmed in the PLC with functions calling the ADEX controllers as necessary. The ADEX controllers, along with supporting library functions, were installed in the ADEX CM module, and finally, a PID backup control was programmed into the PLC to come into action in the event that a problem was encountered with the communications between PLC and ADEX CM.

With the backup PID controller on PLC, a means of switching between ADEX and PID control was added to the PLC and accessible from the Supervisory Control And Data Acquisition (SCADA) system (for engineers only) principally to allow adjustments to be made to the ADEX system without losing control of the process.

Finally, the SCADA iFix monitoring system was updated to include the extra variables being controlled by ADEX and other variables being taken into account as perturbations by the control system.

Before the ADEX CM was linked in, it was decided first to confirm the Phase I control strategy on PC using an OPC link with the final result to be downloaded to the PLC. This was to ensure that there were no fundamental differences in behavior between Units 1 and 3.

Once the aforementioned work was completed, and the hardware connected, final site testing was carried out by monitoring the Unit 3 performance under ADEX control.

The results obtained are illustrated in the following by Figures 10, 11, and 12.

Figure 10 shows 4 h of evolution of the relevant variables in the attemperation process of line A2. From top to bottom, the variables are as follows:

- (1) Drum pressure, which varies between 140 and 170 bars (third column units on the left coordinate axis), in purple.
- (2) Final steam temperature T2, which varies between 560 and 570.5 °C (first column units on the left coordinate axis), in light green, and its set point value (566°C), in red.
- (3) Power generated, which varies between 135 and 260 MW (fourth column units on the left coordinate axis), in white.
- (4) Attemperation outlet temperature T1, which varies between 425 and 475 °C (second column units on the left coordinate axis), in dark green.
- (5) Position of the attemperation valve, which varies between 0 and 52% opening (units on the right coordinate axis), in dark blue.

Figure 10 shows a period of load increase from 135 MW to approximately 265 MW, where temperature T2 undergoes some variation with a maximum of +4.5° C above the setpoint and a minimum of -5.7° C below the set point. This was within the limits set of +5° C and -10° C although in reality, the upper limit was the more critical. Temperature T1 and the attemperator valve position trend curves also show some variation but by no means excessive. This graph illustrates the trade-off between T2 precision and T1 variation; keeping T2 as close as possible to the desired limits to minimize T1 variation, especially during load changes.

Figure 11 shows ADEX performance over an 8-h steady state period on lines A1 and A2 with some variations in load. From top to bottom, the variables are as follows:

- (1) Power generated, which varies around 250 MW within a band of ± 12 MW (fourth column units on the left coordinate axis), in white.
- (2) Temperature T2 of line A1 (light green) which varies slightly around its set point (red) of 566°C, (first column units on the left coordinate axis).

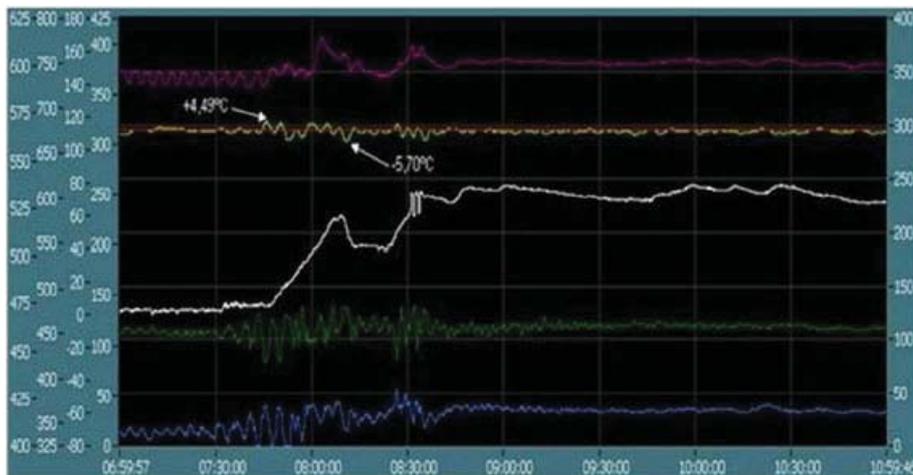


Figure 10. Change of load under ADEX control line A2.

- (3) Temperature T2 of line A2 (light green) which varies slightly around its set point (red) of 566°C, (second column units on the left coordinate axis).
- (4) Drum pressure, which varies between 150 and 158 bars (third column units on the left coordinate axis), in dark blue.

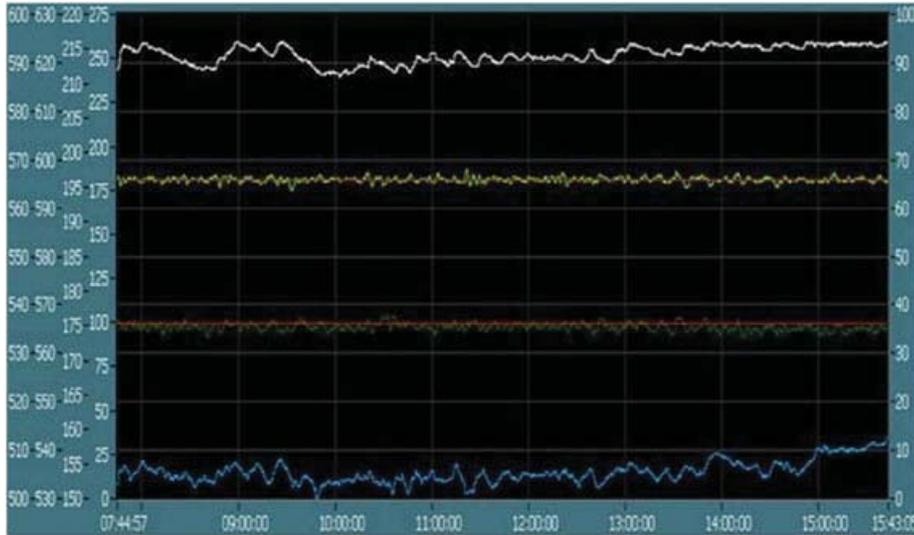


Figure 11. Lines A1 and A2 under steady state conditions and ADEX control.

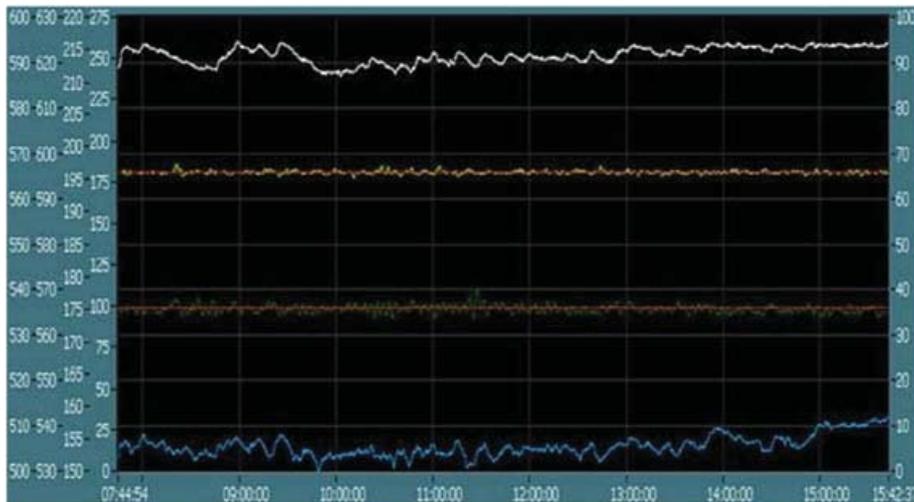


Figure 12. Lines B1 and B2 under steady state conditions and ADEX control.

Table I. Statistics for T2 temperature for all four lines under ADEX control.

T2	ADEX T2 control statistics		
	Mean	SP	SD
Line A1	565.9	566	0.5659
Line A2	565.5	566	0.7915
Line B1	565.9	566	0.3554
Line B2	565.8	566	0.7732

ADEX, adaptive predictive expert; SD, standard deviation; SP, set point.

Figure 12 presents trend curves of the same variables of Figure 11, with the same time scale but related to attemperation lines B1 and B2.

As shown in Figures 11 and 12, similar satisfactory ADEX control performances has been obtained for attemperation lines A1, A2, B1, and B2 during steady state operation. Statistics for the 8-h period shown in the figures are presented in Table I.

9. CONCLUSIONS

The final implementation of the ADEX CM controller module, working in conjunction with the PLC was carried out on time and within the budget available for this project.

After experimentation, a satisfactory compromise was reached between precision in controlling T2 with all that this implied in terms of adjusting T1 frequently with a reasonable variation of T1 thereby ensuring a minimum of stress on the attemperation pipework and of course, the boiler.

The results from Phase I of this project had shown a 50% improvement on the existing system and the results obtained from Phase II have retained a similar performance profile although T2 performance was adjusted to bring T1 variation down to acceptable levels.

The integration of the robust ADEX solution was achieved without modifying the existing control architecture, the introduction of a PLC was only necessary because the existing control was performed by two-loop controllers. Had the existing control been carried out by a PLC, then the only addition would have been the ADEX CM. This makes ADEX controllers particularly attractive for retro fit applications giving maximum control performance and physical robustness with a minimum of intrusion.

Further improvements in final steam temperature control could be achieved by improving

- Master pressure control—improving the balance between electrical load and heat input to the Furness.
- Reducing the variation in feed regulation valve differential pressure.
- Optimizing boiler damper controls to reduce effect of uneven distribution of hot gasses over boiler tubes.

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