Progetto Energia's
50-MW combined-cycle
cogeneration plant
at Melfi, Italy, shown
during construction.

Dynamic Model of Italy's Progetto Energia Cogeneration Plants Aims to Better Predict Plant Performance, Cut Start-up Costs

Over the next four years, the Progetto Energia project will be building several cogeneration plants to help satisfy the increasing demands of Italy's industrial users and the country's demand for electrical power. Located at six different sites within Italy, these combined-cycle cogeneration plants will supply a total of 500 MW of electricity and 100 tons/hr of process steam to Italian industries and residences.

To ensure project success, a dynamic model of the 50-MW *base unit* was developed. The goal established for the model was to predict the dynamic behavior of the complex thermodynamic system in order to assess equipment performance and control system effectiveness for normal operation and, more importantly, abrupt load changes.

In addition to fulfilling its goals, the dynamic study guided modifications to controller logic that significantly improved steam drum pressure control and bypassed steam desuperheating performance. Simulations of normal and abrupt transient events allowed engineers to define optimum controller gain coefficients.

The dynamic study will undoubtedly reduce the associated plant start-up costs and contribute to a smooth commercial plant acceptance. As a result of the work, the control system has already been through its check-out and performance evaluation, usually performed during the plant start-up phase. Field engineers will directly benefit from this effort to identify and resolve control system "bugs" before the equipment reaches the field.

Each power plant site will have one or more nearly identical 50-MW combined-cycle units burning natural gas. The 50-MW *base unit* will be installed singularly at two sites (Sulmona and Rivalta) and side by side at each of the remaining four sites generating 100 MW each (Cassino, Melfi, Termoli and Pomigliano). The Melfi unit (see photo) has been placed into commercial operation and the remaining units will be commissioned on a schedule of one unit every two months until all 10 units have been installed.

Project constraints demanded a thorough technical and economical analysis for selecting the combined cycle configuration. The general approach was to design a single *base unit* that would be adaptable to the six different sites with only minor modifications. The advantage of this approach would be to have nearly all engineering activities performed on only one unit, and then purchase 10 identical components, saving considerable cost.

High thermal efficiency, rapid dispatch and high plant availability were key reasons why the natural gas combined-cycle plant was chosen. Other favorable attributes of the combined-cycle plant contributing to the decision were:

- Minimal environmental impact;
- A simple and effective process and control philosophy to result in safe and easy plant operation;
- A choice of technologies and equipment proven in a large number of applications.

Dynamic simulation of the combined-cycle base unit was pursued as an effective way for assessing equipment and control system behavior, capabilities and limitations during normal and severe plant operation. The goal of the modeling effort was to simulate all foreseen transient events to ensure that:

- Plant process equipment would always operate within its safe operating envelopes;
- Steam drum levels are reasonably well behaved and remain within safe operating limits;
- Control system performance is acceptable;
- Untested control philosophies perform as expected.

PLANT DESCRIPTION

Figure 1 (Pg. 20) shows a simplified process flow diagram of the 50-MW combined-cycle base unit common to all the plants. A LM6000 aero-derivative gas turbine engine (GTE) packaged by FiatAvio is coupled to a two-pressure Foster Wheeler heat recovery steam generator (HRSG). A portion of the low-pressure steam generated in the HRSG can be diverted to the steam consumers (up to a maximum of 10 tons/hr) while the remaining steam flow is expanded in a steam turbine.

The steam and gas turbines drive a single electric generator at 50 Hz through a common generator drive shaft utilizing a disengaging clutch for steam turbine start-up. At full output, the GTE produces 40 MW and the steam turbine produces 11.6 MW supporting the parasitic losses and the design generator load of 50 MW.

The unit is designed for outdoor installation and is complete including all auxiliary services and systems: instrument air production, demineralized water generation, closed cooling water circuits, fire-fighting facilities, auxiliary boiler for start-up, and an emergency diesel generator. A common building will house the control room, the instruments and electrical rooms.

LM6000 Gas Turbine

The LM6000 gas turbine is a General Electric engine packaged by FiatAvio. It is a 40-MW aero-derivative two-spool engine with a 29:1 overall pressure ratio and a 1341 °C firing temperature. The low-pressure (LP) shaft rotates at a fixed speed; the high-pressure (HP) shaft with load. The HP spool consists of a two-stage air-cooled gas turbine powering a 14-stage HP compressor with five stages of adjustable geometry. The LP spool consists of a 5-stage air-cooled turbine powering a 5-stage LP compressor and the generator load.

Steam Components

The GTE exhaust gas flows horizontally through an HRSG manufactured by Foster Wheeler Italiana, S.p.A., passing its heat to the vertical steam coils. The horizontal design was selected to avoid the need for boiler water circulation pumps. The HRSG generates both HP and LP steam for electrical power generation as well as supplying LP steam to unit battery limits for cogeneration. Both the HP and LP steam circuits consist of economizer, evaporator, and superheater tube bundles.

The HP and LP evaporators utilize conventional steam drums with the LP drum degassing the entering condensate. The LP economizer features a feedwater preheater and control logic to maintain a minimum stack temperature. Attemperation is used before the final HP superheating tube bundle for final steam temperature control.

Both the HP and LP steam is expanded in a single-section steam turbine with an induction nozzle for LP steam admission. Steam admission and bypass valves provide for steam-drum pressure control, steam turbine frequency control and total steam bypass for start-up and turbine trip situations. The bypassed steam is cooled with desuperheaters before entering the condenser.

In order to minimize environmental impact, a forced-draft air surface condenser was selected to avoid vapor plumes and comply with stringent plant profile regulations. In fact, the fixed condenser pressure was chosen (0.13 bar abs.) as a compromise between thermal performance and plant profile constraints.

CONTROL SYSTEM

The overall objective of the combined-cycle control system is to maintain a desired generator load or frequency while maintaining pressure and level within the HP and LP steam drums. Under normal operation, the steam cycle extracts the maximum energy from the GTE exhaust gas and converts it to shaft work to drive

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the generator and steam for cogeneration.

To accomplish this, HP and LP boiling temperatures and hence steam drum pressures are allowed to *float* with exhaust gas temperatures within upper and lower limits. This control strategy establishes the gas/steam turbine work split for all operating conditions and results in the most efficient combined-cycle operation.

The combined-cycle control strategy and its resulting dynamic behavior is the result of the separate actions of six independent controllers:

- Gas turbine control;
- HP and LP drum pressure controls;
- HP and LP drum level controls;
- Steam turbine speed control.

Other controllers such as for HP steam attemperation and bypass steam desuperheating basically provide for equipment protection and do not significantly contribute to combined-cycle dynamic behavior.

Gas Turbine Control

The LM6000 is controlled by a Master 900 SEPA control system. The Master 900 provides frequency and power control under normal operation while protecting the engine by limiting key engine parameters. The control ensures smooth transitions for all modes of operation: start-up, shutdown, planned and unplanned load changes and takes the necessary protective actions under abnormal conditions.

Using hierarchical logic, the Master 900 will control generator frequency or power provided that the following engine parameters remain within prescribed limits:

- HP spool shaft speed and acceleration;
- LP turbine inlet gas temperature;
- HP compressor exit temperature;
- HP compressor exit pressure;
- Engine fuel flow.

If any of these parameters reaches its limiting value, the control's other priorities are realigned in order to maintain that parameter's limit.

The Master 900 also schedules the LP inlet guide vanes, compressor bleed valve position, and HP compressor stators to achieve optimum engine performance while maintaining compressor stability under varying operating conditions.

The SEPA system offers frequency or power control for the two types of generator service, *synchronous* and *isochronous* operation. Synchronous operation occurs when the generator is supplying power to an electric utility grid. In this case, the grid sets the frequency and the combined cycle regulates power output. Isochronous operation occurs when the generator is supplying power directly to a specific load such as a factory. In this mode the combined cycle does control frequency and the attached load determines the generator output power.

In synchronous mode, the Master 900 provides direct power regulation utilizing both proportional and integral error correction as well as conventional droop control with only a proportional component. Set point load changes are limited through a linear ramp to protect steam component life by limiting thermal cycling. Generally, transients in this mode are smooth, slow events.

In isochronous mode, the Master 900 actively controls generator frequency through an isochronous governor. Unlike synchronous mode, abrupt disturbance in load and hence frequency will result in abrupt disturbance in the combined-cycle operating conditions, limited only by the control's shaft acceleration limit and governor dynamics.

Steam Turbine Frequency Control

The steam turbine has its own speed or frequency governor. A standard controller with proportional, integral and derivative components (PID) acts on the HP and LP steam turbine admission valves to maintain the set point speed.

During isochronous operation, the steam turbine frequency set point is biased above that of the GTE so that the steam turbine governor acts only if the GTE governor is not maintaining the set point. Since the GTE and steam turbine

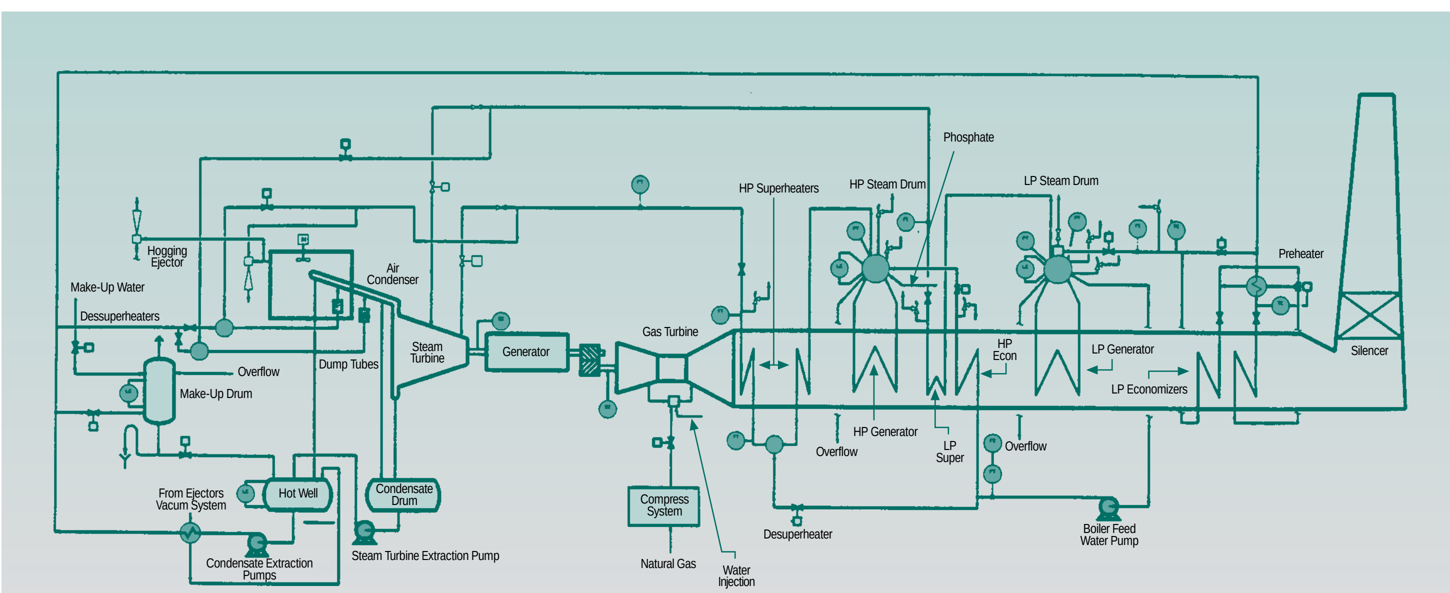
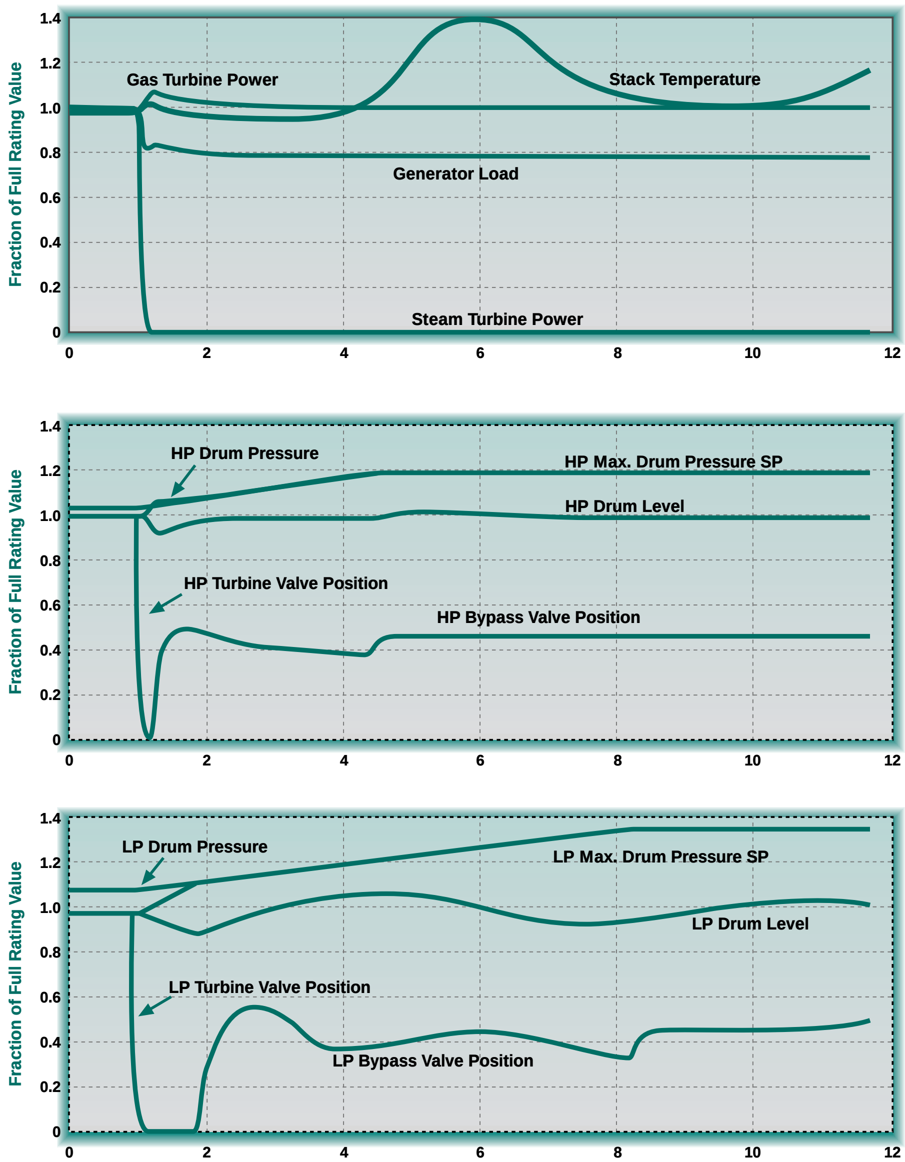


Figure 1. Process Flow Diagram of the Progetto Energia Combined Cycle

Figure 2. Simulation Results of Full Load Steam Turbine Trip



shafts are rigidly connected through the generator, the steam turbine governor can be viewed as a secondary or safety governor which usually becomes active during large load variations.

The HP and LP steam turbine admission valves are also controlled by the steam drum pressure controllers. The control logic selects the minimum commanded position from the pressure and the frequency controllers.

Steam Drum Pressure Control

When not exporting steam for cogeneration, pressures in both steam drums float with exhaust gas temperature within minimum and maximum limits. The steam drum pressure controllers (HP and LP) hold the steam turbine admission valves fully open and the steam turbine bypass valves fully closed. Once a limiting drum pressure is reached, either the admission valve is closed to maintain the minimum pressure or the steam turbine bypass valve is opened to maintain the maximum pressure. In addition to maintaining the absolute minimum and maximum pressures, the pressure controllers also limit the rate of change of steam drum pressure to minimize pressure cycling.

During a transient, if the drum pressures exceed the time-dependent pressure set point, the controller will act on the appropriate valve (bypass valve for exceeding rise rate, admission valve for exceeding fall rate). This logic, called tracking, has a sort of anticipating effect on pressure, because regulation of the valves occurs before the drum pressures reach their absolute lowest or highest values.

In cogeneration mode, the tracking logic acts on the HP section only; the LP pressure controller maintains the LP drum pressure at the fixed pressure of the battery limits.

Steam Drum Level Control

The water level in the steam drums is controlled by regulating inlet boiler feedwater (BFW) flow. The HP drum utilizes a three-element level controller for normal operating steam flows and a single-element controller for low-flow operation.

The three-element PID controller adjusts the BFW valve based on steam drum level, outlet steam flow rate and inlet BFW flow rate. The BFW controller set point is reset by the outlet steam flow and the signal coming from the level controller. This system ensures that level changes due to pressure changes only (i.e. swelling) do not cause BFW flow rate adjustments at constant steam production conditions. The LP drum employs a single-element level controller.

Bypass Steam Attemperation

The superheated steam diverted to the condenser by the bypass valves when they lift must be cooled below 110 °C before entering the condenser. The attemperation must respond very quickly since the bypass valves can open in a step fashion. An algorithm is utilized to calculate the required feed water flow rate for a given steam flow rate and enthalpy. The calculated value is sent to the attemperation controller as the set point.

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DYNAMIC MODEL REPRESENTATION

The dynamic model of the plant was constructed using a general-purpose power plant dynamic modeling software package called PC-TRAX. The platform offers a real-time dynamic modeling environment with an extensive library of predefined power plant component modules. If a component is unique, PC-TRAX offers the flexibility of creating a custom component representation using a standard dynamic modeling language (ACSL™).

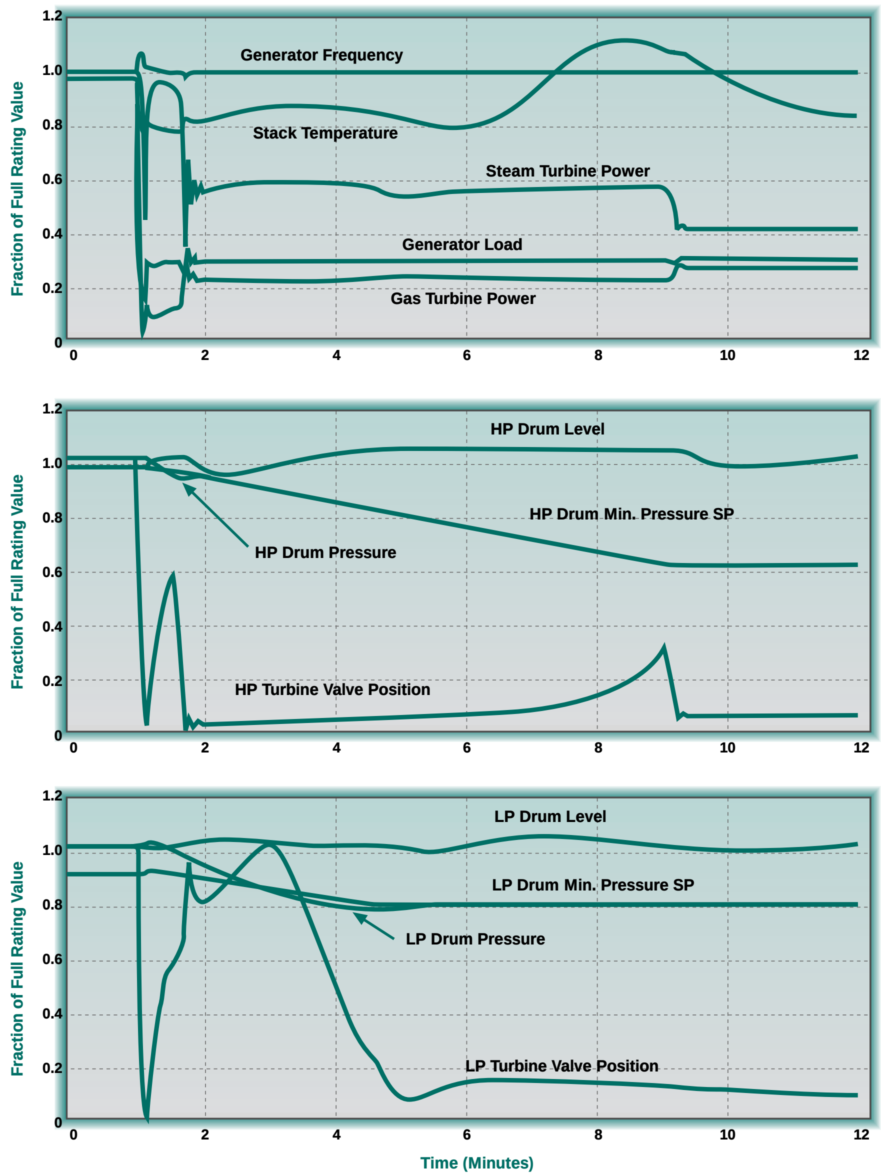
The software constructs the unsteady differential equations representing mass, energy and momentum conservation as well as the necessary algebraic equations defining component characteristics for each of the component modules. The differential equations are then reduced to a system of first order equations and solved simultaneously with a Euler numerical integration. The dynamic event initiates from the steady-state point defined by the engineer.

The Progetto Energia combined-cycle plant is represented by over 125 interconnected component modules. Each component's specific physical and operating information was input to achieve a faithful dynamic component representation. Not all of the plant's components could be accurately represented by a generic module such as portions of the gas and steam turbine control logic. For these, custom representations were developed.

All plant components were represented dynamically with simplifications being applied where appropriate. Since the steam cycle responds slowly (minutes) and the gas turbine quickly (seconds), the combined-cycle dynamic behavior is predominately influenced by the steam cycle dynamics. With this in mind, very few simplifications were applied to the steam components.

Most of the combined-cycle control systems were represented using standard SAMA blocks. Custom ACSL was written to represent the steam drum pressure tracking logic and the bypass valve steam attemperation logic.

Figure 3. Simulation Results of Full Load Grid Trip



Modeling simplifications were made, however, regarding the gas turbine and its control. Instead of modeling the individual gas turbine components (compressor, burner, turbine), the engine was represented by simplified correlations for engine output power, exhaust-gas temperature and exhaust-gas flow rate. The SEPA control was simplified by modeling only the frequency and power control loops, since the control's engine protection and limiting logic does not become active during the simulations of interest.

To ensure that these simplifications would not jeopardize model accuracy, dynamic gas turbine traces from the manufacturer were used to calibrate the GTE model. The control's coefficients (proportional, integral, and derivative gains) were tuned so that the model's response matched that of the manufacturer.

RESULTS

The dynamic model was sufficiently exercised to ensure accurate and reliable results. Transients were selected for which the behavior of certain cycle parameters was known from experience or analytically predictable. Once the model was validated, a series of transient events were simulated to accomplish the objectives set forth for the project. These events included:

- Load variations during synchronous and isochronous operation;
- Abrupt grid disconnections to minimum loads;
- Steam turbine trips in synchronous and isochronous operation.

The behavior of key cycle parameters during a steam turbine trip is summarized in Figure 2 (Pg. 21). The trip was initiated at 100% output power while the generator was attached to the electrical grid (synchronous operation). The trip causes both the LP and the HP steam admission valves to rapidly close.

The gas turbine attempts to compensate for the loss in power output, but the GTE control constrains the GTE to its maximum power limit. Within seconds the pressure in the bottled-up steam drums rises above the pressure tracking set point and both HP and LP bypass valves open controlling the pressure rise rate and ultimately the absolute maximum pressure (see mid and bottom plot).

This event causes a significant upset to the HRSG's steam duty as is evidenced by the stack temperature variation (top plot of Figure 2). The steam duty disturbance is a direct result of the level controllers significantly altering BFW flow to both drums in an effort to maintain drum level during the upset. Events like this guided the tuning of the level controller's gain coefficients.

Figure 3 summarizes the combined-cycle behavior during an abrupt grid disconnection--such as resulting from the opening of the grid breaker. The disconnection initiates from the 100% output power condition for which a portion (15 MW) is being supplied directly to a factory load. Once disconnected, the combined-cycle control transitions immediately to isochronous operation and continues to supply the factory load.

Due to the step change in load, the GTE fuel valve, HP and LP steam turbine admission valves quickly close to reestablish the generator frequency. Unlike the steam turbine trip transient, closure of the steam turbine admission valves do not cause the steam drum pressures to rise. In this case, the GTE absorbs the largest portion of power variation, resulting in a steep reduction in exhaust gas temperature. In fact, both drum pressures continually fall as shown by Figure 4.

Once the steam turbine frequency controllers lift their constraints on the steam turbine admission valves, the steam drum pressure controllers begin to reopen them. This, in turn, causes the drum pressures to fall more rapidly until their limits are reached, at which point the pressure controllers begin to close the steam turbine admission valves once again. The minimum absolute drum pressures are finally reached and the valves are adjusted to their final steady-state positions. As expected, drum levels and hence stack temperature are upset due to the cycling of the steam turbine admission valves. However, the level controllers hold the variation to within safe limits before eventually stabilizing it.

BENEFITS TO PROJECT

Redesign of Steam Drum Pressure Control Logic

The HP and LP steam drum pressure tracking logic computes a minimum and maximum drum pressure set point (SP) dependent on the measured steam drum pressure. As previously described, the control logic is designed to not only limit absolute minimum and maximum drum pressures, but also limit the rate of pressure change (increasing or decreasing).

This pressure tracking technique generates two-time dependent pressure SPs (minimum and maximum) that bracket the current measured drum pressure. If the measured pressure comes in contact with either SP, the pressure controller actuates either the steam turbine admission valve to maintain the minimum limit or the steam turbine bypass valve to maintain the maximum limit.

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Figure 4. Improved Performance of Pressure Tracking Logic For 20% to 100% Load Increase on Grid

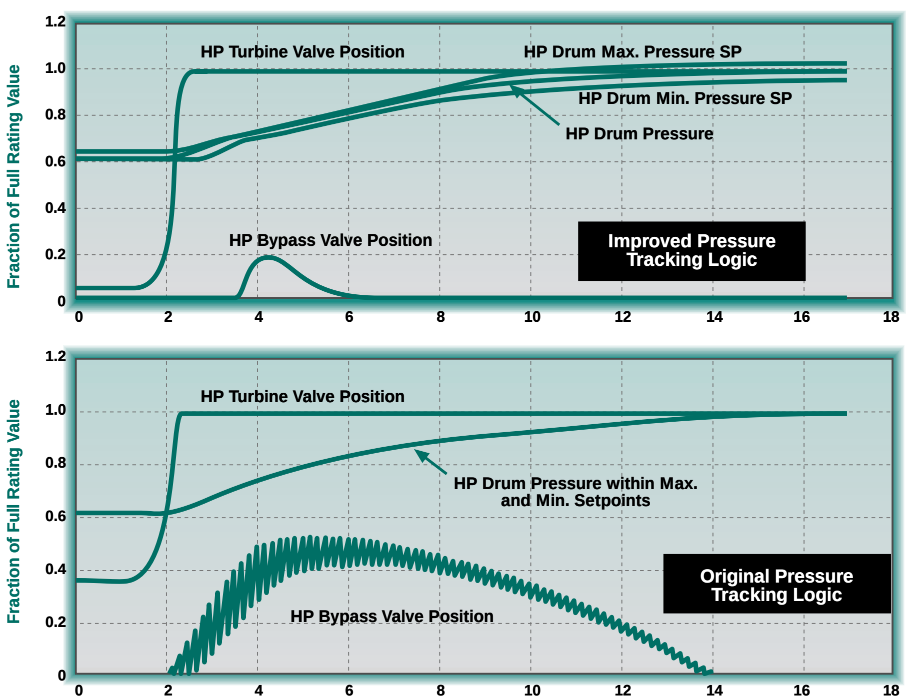
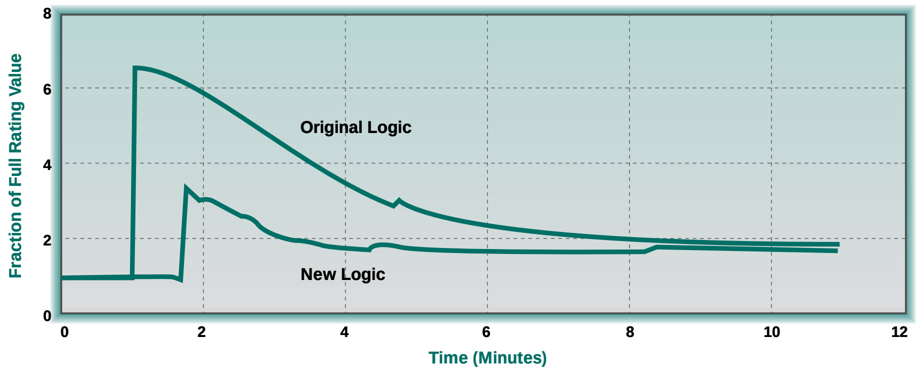


Figure 5. Improved Performance of Attemperation Control Logic



Initially, the proposed SP computation logic held a given SP for a specified time after it was computed. The computation was based on adding and subtracting a limiting tolerance to the drum pressure PV. This technique resulted in rather discrete, stepwise SP curves. The bottom plot of Figure 4 shows these curves generated by the logic for a 10 to 50 MW load increase transient.

As the drum pressure reaches the limiting SP curve, the appropriate valve was stroked in an erratic oscillatory fashion (Figure 4). The simulation also brings out the fact that the tolerance between the SP curves is too small since the drum pressure curve is contacting both of them and hence both the steam turbine admission and bypass valves are being stroked simultaneously. This behavior would lead to increased steam component cyclic stress and premature equipment failure.

Dynamic simulation guided the redesign of this logic by evaluating the performance of other prototype logics. The final design proved to be the most effective and is based on an integration technique of the pressure limit derivative and an increased tolerance between the minimum and maximum SP curves. The new logic generates smooth SP curves resulting in smooth valve movements, as can be seen in the top plot of Figure 4 for the same transient event.

Tuning of Control System

The dynamic simulation has been very useful in control system tuning. The prediction of plant behavior during typical and atypical operation allowed us to optimize controller gains and control philosophy.

The tuning of the bypassed steam attemperation control loop is an example of the improvements achievable through control tuning and control logic optimization. Figure 5 illustrates the bypassed steam temperature entering the condenser after attemperation for the steam turbine trip transient discussed previously. During this event both the HP and the LP steam is bypassed.

Since the bypass valves open rapidly from their fully closed positions, attemperation of these streams must be very responsive. Instead of temperature, the SP of the controllers is the feedwater flow rate which is computed from an algorithm based on the bypassed steam flow rate and enthalpy. Improvements to the algorithm and tuning of the gain coefficients resulted in the temperature profile improvement shown in Figure 6 for this severe operational event.

CONCLUSIONS

The benefits from the practical application of dynamic modeling are clearly illustrated in this paper. The Progetto Energia project used a dynamic model of their common plant design to evaluate integrated plant operation and control system performance. The engineering investment paid off when the model identified the drum pressure tracking logic problem and evaluated the alternate control strategies. Other benefits include improved bypass attemperation logic and the tuning of all major control loops.

No other technique or method gives the pre-start-up insight into integrated plant operation, response, stability, control system performance, and limitations as does a comprehensive dynamic model.

Dynamic models have two overlapping uses: (1) pre-start-up plant/controls checkout and (2) plant equipment/control system development. The maximum benefit from dynamic models is achieved when the model development is coincident with plant design. During the plant design stage, the model can be used as a development tool guiding the design by focusing on overall integrated plant operation. During control system design, it can evaluate controller performance and quantify difficult control areas within the plant. Finally, it can serve as a pre-start-up checkout and tuning tool for the established control system. ■

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