Closing the Performance Loop

How Whiting Clean Energy uses GE's CLOC™ System For Optimal Generation and Efficiency

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[Editor's Note: In the previous issue of ORBIT (Volume 25, No. 1, 2005), our article on performance monitoring for gas turbines (pp. 64-74) presented a tutorial on thermodynamic performance monitoring and briefly introduced readers to EfficiencyMap™ software and its online optimizer module. Here, using actual results achieved by Whiting Clean Energy, we show how these products can effectively be used as part of a closed-loop optimization and supervisory control system to improve overall plant efficiency along with optimal generation within constraints.**]**

Introduction

GE Energy's Closed Loop Optimal Control (CLOC™) system was installed in 2003 at the Whiting Clean Energy (WCE) cogeneration facility in Whiting, Indiana. The objectives of the project were threefold:

1. **To continuously optimize** electric power generation and steam production by closely matching the dispatched generation and minimizing over-generation;
2. **to protect against** constraint violations, such as NO_X emissions above the allowable limit and minimal steam flow to the steam turbine;
3. **to improve** plant heat rate and efficiency.

This article describes how the CLOC system works, how it was applied at WCE, and the results obtained.

THE CLOC SYSTEM REDUCED VOLUNTARY OVER-GENERATION BY 90% (OR 3.7 MWH/H ON AVERAGE)

Closing the Performance Loop

GE's CLOC system, which utilizes real-time performance monitoring and optimization, is commonly used to optimize the operation of simple- and combined-cycle plants for maximum profitability. The system determines the most profitable way to operate such plants given "time of day" or "dynamic" fuel variations, electricity and steam prices, load levels, equipment degradation, and operational constraints. In fact, the more dynamic the plant operation, and the more complex the process, the greater the opportunities for CLOC optimization and associated customer profit or margin enhancement.

As applied at WCE, the CLOC system ensures that certain controllable operational limitations, such as NO_x levels and minimum steam turbine steam feed, are not violated. It also matches the net generation dispatch closely, thereby minimizing voluntary over-generation. In addition, the plant is operated at an improved heat rate by employing an online thermo-economic optimizer. Exact control of generation is important at this site since the plant runs most economically when there is neither over-generation nor under-generation.

As will be shown, the CLOC system reduced voluntary over-generation by 90% (or 3.7 MWh/h on average) without causing any under-generation. Also, the ability to protect against certain operational constraint violations proved to be very effective using the CLOC System.

Whiting Clean Energy cogeneration facility in Whiting, Indiana, U.S.A.

Why Close The Loop?

Continuously maximizing plant efficiency is difficult today because power generation by merchant power producers (both simple- and combined-cycle) and cogeneration facilities involves operating challenges from fluctuations in prices and costs. Host steam demand is continually changing, requiring continuous action to ensure that scheduled (contracted) sales to the electric grid and the steam host are met. These challenges are further complicated by environmental and operational constraints, along with other limitations imposed on the plant. The resulting complexities can make it very difficult for a plant to reach its goal through manual control alone.

The installation of an online optimizer, such as the one included in GE's EfficiencyMap™ software, can help by calculating optimum steady-state setpoints for maximum efficiency of both steam and power production. However, while an online optimizer may provide optimal setpoint information, *it does not close the loop* – it instead relies upon manual implementation of recommended setpoints.

Another consideration when optimizing is the dynamic nature of plants. For example, a cogeneration facility has no direct control over host steam demand, nor captive power use by a power host. Such demand variations and process dynamics in both electrical and steam systems translate to optimal dynamic operating points that differ from optimal steady-state operating points. An effective optimizer must be capable of addressing these dynamic fluctuations.

Prior to the installation of the CLOC system, WCE operators manually adjusted their control systems in order to follow changes in both steam and power demands. It was recognized that manual intervention to continually adjust setpoints was impractical if the plant was to realize its full optimization potential. Thus, a fully closed-loop optimization strategy was pursued to ensure that (within mechanical system limits):

- Generating targets could be met dynamically (block tie-line control) at the point of sale (not at the generators), resulting in a significant reduction in voluntary over generation.
- Steam production could match demand continuously, thereby improving the steam availability while protecting the steam turbine against low steam flow.
- Some operational constraints could be actively controlled, thus reducing the number of reportable non-breach incidents.
- Interaction requirements for operators could be reduced. Implementation of setpoint adjustments could be automatic, resulting in continued operation at optimum settings for maximum efficiency.
- Dependence on operators to monitor and adjust CLOC-controlled units while starting additional assets could be eliminated. The CLOC system could account for the net output of all generators, whether under system control or not, thus ensuring that dispatched generation could be met accurately.

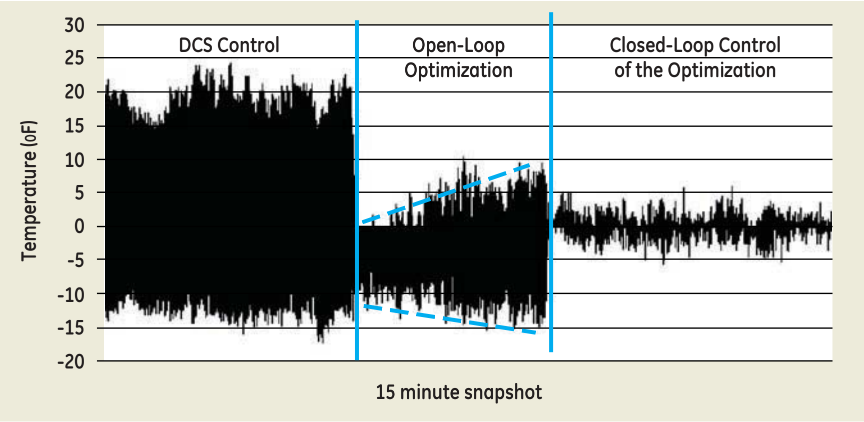

Figure 1 – **Temperature variation in a fired reformer showing dramatic effects of closed-loop optimization (right) when compared with open-loop optimization (center) and no optimization (left). Note how open-loop optimization drifts over time due to operator distractions.**

About Whiting Clean Energy

Whiting Clean Energy is a 525-MW combined-cycle cogeneration plant with two gas-fired combustion turbine units, duct-fired heat recovery steam generators (HRSGs), and a condensing steam turbine with a closed cooling water system. The facility sells high-pressure steam to its host, BP's Whiting Refinery. All of the power is sold on the grid.

The combustion turbines are GE Model PG7241FA (MS7001FA), which are fired on pipeline-quality natural gas. The fuel conditioning system consists of compressors, particulate filters, pre-heaters, and coalescing filtration for the heavy hydrocarbon removal from the natural gas prior to combusting the fuel in the turbines. The fuel compressors are three 50% capacity units. A Dry Low NO_x combustion system is supplied on each turbine for emissions control. Each turbine is rated at 166.6 MW (ISO conditions).

The HRSGs connected to each combustion turbine utilize the hot exhaust gases to generate high-pressure and low-pressure steam and to preheat the feed water. The high-pressure steam conditions are 1300 psi and 860° F. The low-pressure steam is utilized for pegging steam for the external deaerators. Natural gas-fired duct burners provide each HRSG with the ability to double the steam production. The duct burners consist of a burner management system with flame scanners and fuel control valves. A Selective Catalyst Reduction (SCR) System is provided with each HRSG and consists of an anhydrous ammonia system with a storage tank, vaporizers, and associated injection equipment. Each HRSG has its own stack with a continuous emissions monitoring system.

The steam turbine is a GE down-flow condensing unit with a closed cooling water system. The turbine auxiliary equipment consists of a lube oil system, hydraulic system, steam seal system, and a Mark V control system. There is also a steam-turbine-bypass letdown valve, which dumps the steam directly to the surface condenser. The generator is hydrogen cooled with a rating of 213 MW.

COMPARISON OF CONTROL MODES

- ### DCS Control (No Optimization)

  In DCS control, the operator implements setpoints manually, based on historical settings or a series of adjustments to bring the plant to the best-known operating condition, without assistance of optimization models or tools. Large variations in performance are possible, due to changing dynamics from demand or steam generation, and the difficulty in making such adjustments continuously and optimally.

- ### Advisory (Open-Loop) Optimization

  In advisory mode, a supervisory system (such as GE's EfficiencyMap software and its online optimizer module) generate recommended optimal setpoints every 3-5 minutes. However, operators are expected to implement these setpoints manually. While an operator can initially move the plant towards an improved operating point, the vigilance required to continually make such manual setpoint changes will generally deteriorate with time, and the plant will slowly "drift" from its optimal operating point. There are numerous tasks incumbent upon most operators – not just setpoint adjustments – along with numerous distractions. This helps explain the deterioration of advisory-only optimization over time and the desirability of closed-loop optimization.

- ### Closed-Loop Optimization

  By automatically implementing the recommended optimal setpoints supplied by the optimizer module, not only can a plant operate closer to its optimal operating point, but this advantage can be maintained over time. Variation in control of the process is dramatically reduced. The process is now stable and more efficient with greatly reduced operator interaction.

Figure 1 illustrates the variance in these three control modes for a fired reformer. The optimization algorithm required 2400 setpoint changes per hour, underscoring why open-loop optimization is neither practical nor sustainable for many optimization applications.

THE **OPTIMIZER MUST** THEN **MEET** POWER AND STEAM DEMANDS **WHILE MINIMIZING** OVERALL HEAT RATE OF THE FACILITY.

How CLOC Works

In order to reach the stated objective of lowered generating costs through both reduced fuel consumption and minimized average over-generation, automatic supervisory-level control is applied to the critical generating assets. The CLOC system actively sends generating setpoints to the governor for each turbine generator, as well as firing–rate setpoints to the burner management system of the duct burners.

The process itself is straightforward: at any point in time, the advanced supervisory control knows how much power generation is required to cover dispatch and parasitic load demand and how much extra steam is required to cover host steam demand. These values are fed to the online optimizer with instructions to distribute the power over the available assets and to calculate the firing rates of the duct burners. The optimizer must then meet power and steam demands while minimizing overall heat rate of the facility.

After calculating an online heat and mass balance and reconciling the data (the heat and mass balance errors will be minimized and incorrect measurements recalculated), plant and component efficiencies can be calculated, and thus performance degradation. The CLOC system uses models from GateCycle™ heat balance software, which is widely used in the power industry for design and off-design studies of power plants.

The system analyzes performance at the equipment level (gas turbine, HRSG, steam turbine, condenser) compared to design conditions as quoted by the OEM data as well as data created by models of the entire plant. Based on this analysis, the performance of the equipment is known along with its incremental cost. This data suffices to optimize the generation and steam production at the lowest cost (heat rate), taking operation and environmental constraints into account. The optimal solution found will be a valid operating point for the facility.

The optimal generating targets and firing rates are transmitted to the controller module of the CLOC system. The supervisory controller is charged with bringing the plant towards this optimal operating point on a trajectory that continues to generate steam and power as dispatched, while preventing violation of physical, environmental, and regulatory constraints. However, due to time lag, the previous steady-state optimal operating point may no longer reflect the current dynamic optimal operating point. The steam demand (something the plant has no control over) can change rapidly, directly impacting the output of the steam turbine generator. As such, the controller will bring the plant close to the optimal, steady–state operating point, while ensuring that constraints are not violated and that dispatch (steam and power) requirements are addressed most favorably.

To maintain maximum profitability at Whiting Clean Energy, the CLOC implementation detailed in this article provides five recommended setpoints from its optimizer. Steady-state control would require setpoint changes on the order of once every three minutes (100 total setpoint adjustments per hour). Stable operation, however, does not equate to steady-state control. To maintain *dynamic* control of net generation and plant constraints, regardless of host steam demand, the setpoints will need to be changed even more often, typically every 15 seconds, or 1200 total setpoint adjustments per hour. Clearly, 1200 setpoint changes an hour far exceed an operator's capability. This is the essential difference between an open-loop optimization, where there is reliance upon operators to implement the results of the optimization, and a closed-loop optimization, where implementation is continuous and automatic with the possibility to override the optimization results when operational conditions warrant.

Benefits Achieved

As indicated earlier, the WCE facility operates most economically if under-generation is prevented and over-generation minimized. It is therefore prudent for the plant to generate more than dispatched, but to be as close to dispatch as possible. However, there is an additional complication – ramping due to dispatch changes are normally performed in the final five minutes of the current period and the first five minutes of the next period. Despite these ramps, dispatch must be maintained for both of the one-hour periods.

Prior to the installation of the CLOC system at WCE, average over-generation during a two-month period was 4.2 MWh/h. There was also a 2.1% occurrence of under-generation. Following installation of the CLOC system, over-generation was initially reduced by 52% to 2.0 MWh/h with no under-generation incidences. As the optimization routine was further refined, over-generation was reduced by 90% to less than 0.5 MWh/h. Figure 2 summarizes these results.

THIS IS THE ESSENTIAL DIFFERENCE BETWEEN AN OPEN-LOOP OPTIMIZATION, WHERE THERE IS RELIANCE UPON OPERATORS TO IMPLEMENT THE RESULTS OF THE OPTIMIZATION, AND A CLOSED-LOOP OPTIMIZATION, WHERE IMPLEMENTATION IS CONTINUOUS AND AUTOMATIC.

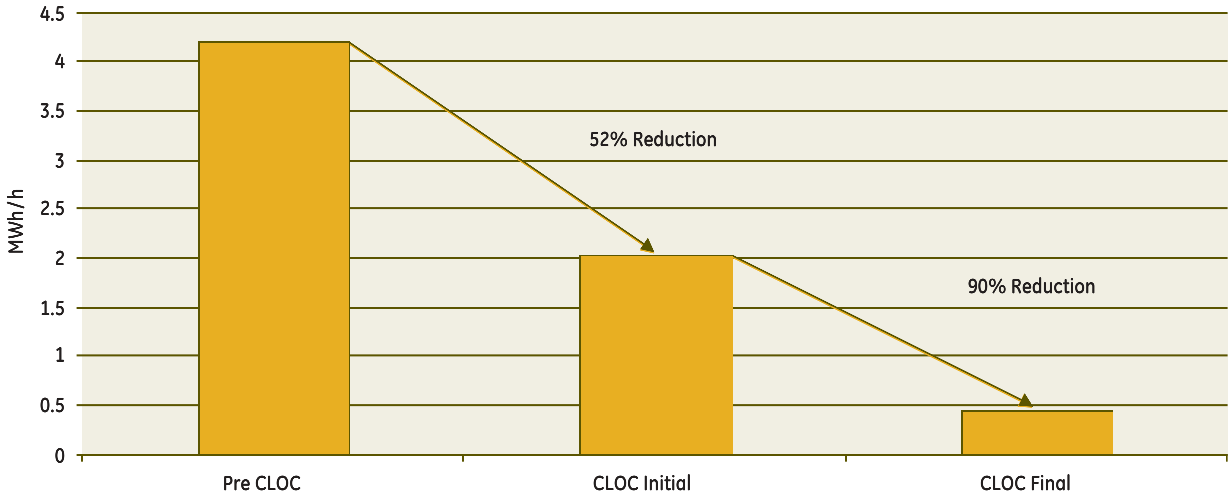

Figure 2 – **Average over-generation prior to and following installation of the CLOC system.**

Error Reduction

A control system works by attempting to minimize the deviation of each control loop from its respective setpoint. If the error is normally distributed about the setpoint (which it usually is), then the controller will operate slightly above the setpoint half the time, and slightly below the setpoint half the time. The implications of this for the WCE implementation are that if the controller were to generate exactly at dispatch, the plant would under-generate half the time, and over-generate half the time, even though the amount of over- or under-generation would be much smaller than previously. However, since under-generation is a very undesirable operating mode for this plant, the control strategy must not just reduce the amount of over-generation, it must prevent under-generation. This can be achieved by reducing variability in the amount of over-generation to the maximum extent possible, and by biasing the setpoint so it is slightly above dispatch. The narrower the error distribution, the smaller the bias will need to be to prevent under-generation.

Figure 3 graphically shows these concepts. The blue vertical line denotes an ideal controller. Generation is always exactly at dispatch with no variability.

In the pre-CLOC distribution (orange), there is a wide variability of over-generation. The data does not reflect a normal distribution, but rather assumes a more non-symmetrical shape known as a Weibull distribution. One would expect such a skewed shape, considering the operators wanted to err on the side of over-generation rather than under-generation, but yet tried to generate reasonably close to dispatch. As previously noted, the average amount of over-generation was 4.2 MWh/h. It is also noteworthy that incidents of under-generation still occurred (twice in a 2-month period).

Initial results with the CLOC system (purple) show that the error assumed the familiar bell-shaped curve, and variability was much less (as noted by the width of the bell curve). To prevent under-generation, a setpoint bias of 2 MWh/h was required (as noted by the mean of the bell curve). With this bias, it was theoretically possible, but statistically highly unlikely, that under-generation would occur.

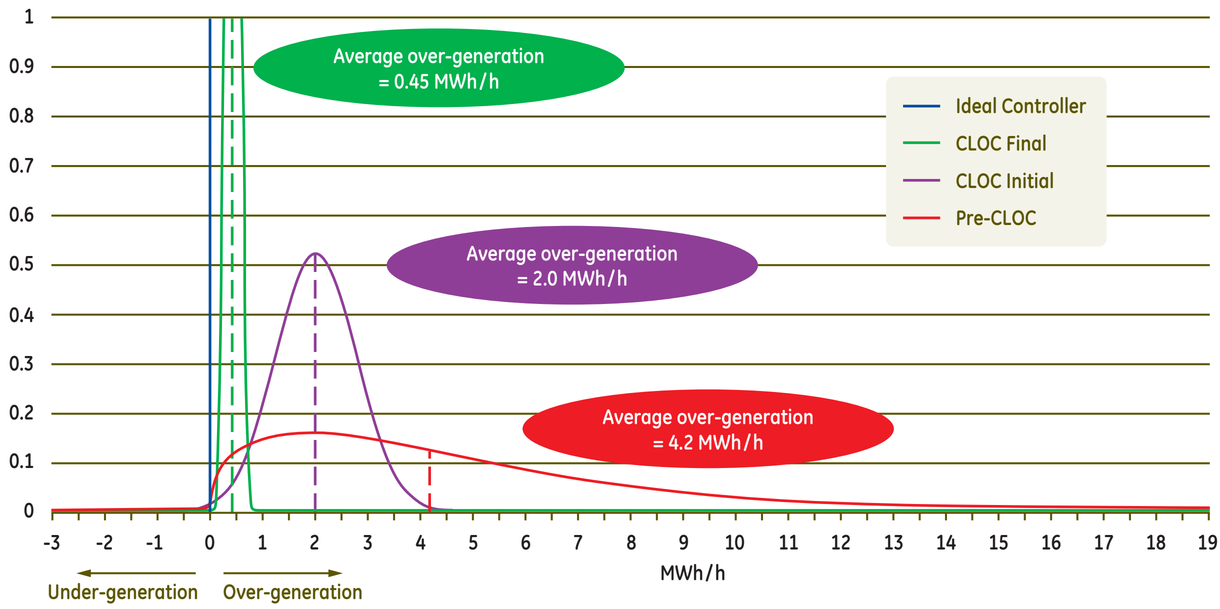

Figure 3 – **Frequency distribution of generating deviation from dispatch.**

BY REFINING THE OPTIMIZATION ROUTINE, VARIABILITY WAS FURTHER REDUCED. THE CLOC SYSTEM WAS ABLE TO LOWER THE AVERAGE OVER-GENERATION TO LESS THAN 0.5 MWH/H WHILE PREVENTING ANY INSTANCES OF UNDER-GENERATION.

By refining the optimization routine, variability was further reduced, as noted by the extremely narrow width of the final CLOC error distribution (green). This allowed the setpoint bias to be reduced to 0.45 MWh/h, with a very low statistical likelihood of under-generation.

Another improvement was related to point-of-measurement for control actions. Prior to installation of the CLOC system, operators controlled the net generation from gross output and manually compensated for internal power consumption. After installation, the CLOC system actually controlled net generation at the point of sale, ensuring the system was making all decisions based upon actual power delivery to the grid.

The cumulative distributions in Figure 4 provide another perspective that clearly shows the dramatic improvement. Prior to CLOC, more than 93% of the over-generation was in excess of 0.6 MWh/h. In comparison, with the final CLOC implementation, less than 7% of the over-generation exceeds 0.6 MWh/h.

In summary, the CLOC system, irrespective of variations in host steam demand (and its direct impact on output from the steam turbine generator), was able to lower the average over-generation to less than 0.5 MWh/h while preventing any instances of under-generation. This is in stark contrast to the pre-CLOC average over-generation of 4.2 MWh/h and several instances of under-generation. The result is significant annual savings for WCE.

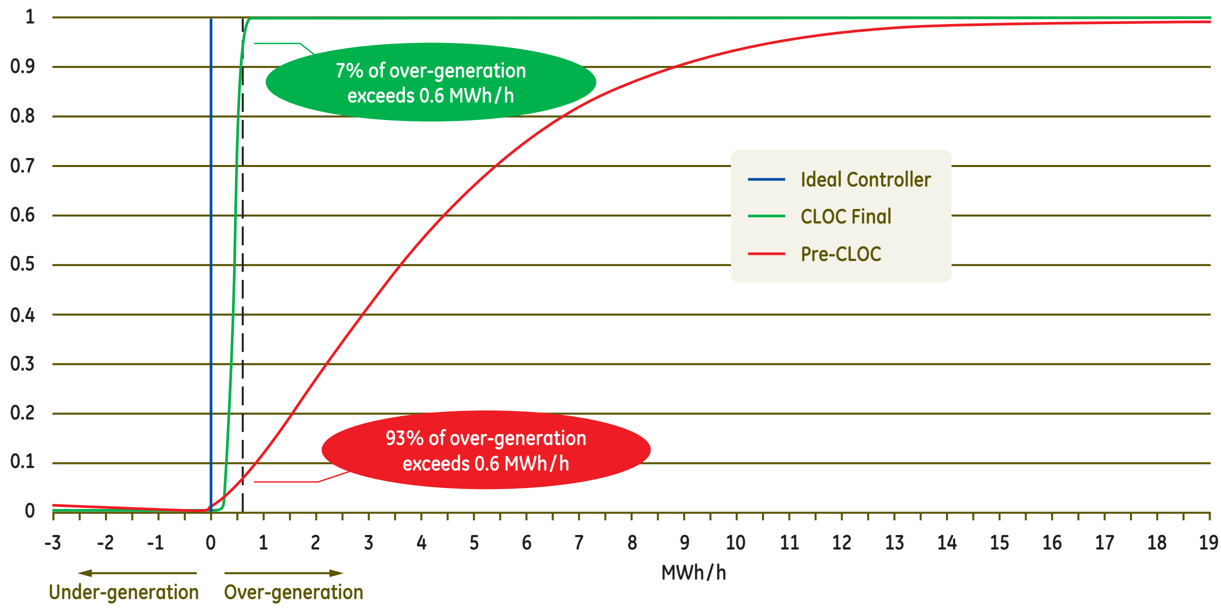

Figure 4 – **Cumulative distribution of generating deviation from dispatch.**

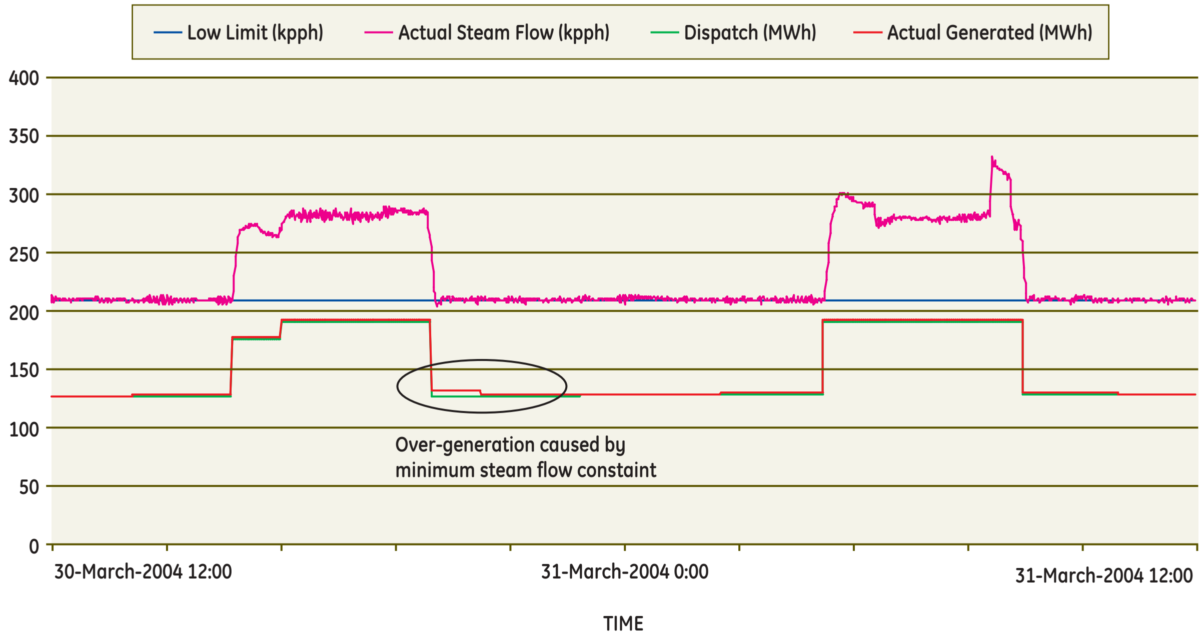

Figure 5 – **The CLOC system automatically prevents steam flow to the steam turbine generator from going below a minimum constraint. Although this results in short periods of over-generation, it prevents damage to the turbine.**

Protecting the Steam Turbine Generator

When dispatch is lowered, less and less steam will be generated by the HRSG's. While still supplying steam to the attached host, the risk exists of starving the steam turbine, causing erratic behavior of the steam throttle valves, and potentially damaging the machine. To prevent this, the CLOC system was configured with a constraint to ensure a minimum steam supply at all times, as measured by a flowmeter to the steam turbine. Figure 5 shows that the reduction in output of the gas turbine (only one was running at this time) was halted when the actual steam supply to the steam turbine hit this minimum limit. Naturally, this caused some over-generation during that period; however, it was preferable to a damaged machine and illustrates why optimization must consider many variables and – in a practical sense – can never eliminate all instances of over-generation. Thus, although the CLOC system does not completely eliminate over-generation, it effectively minimizes it.

The MW output of the gas turbine generators automatically follows rising or falling steam demand from the host. This shows the hierarchy of control priorities embedded in the CLOC system as it conducts its optimization. First, the system will prevent constraint violations. Second, dispatch will be accurately controlled. Finally, if there are sufficient degrees of freedom remaining, the fuel consumption of the facility will be minimized.

Minimizing NO_X violations

Like minimum steam flow, another important constraint in this application is NO_X levels. Though equipped with Dry Low NO_X (DLN) burners, the plant's gas turbines can exceed allowable NO_X levels when gross generation falls below a certain minimum. Unfortunately, this minimum is not constant – it is a function of ambient temperature, humidity, bleed heat, and Inlet Guide Vane (IGV) angle. Mode sequencing (fuel staging) for the DLN combustion system, however, is primarily a function of the combustion reference temperature. Other DLN influencing

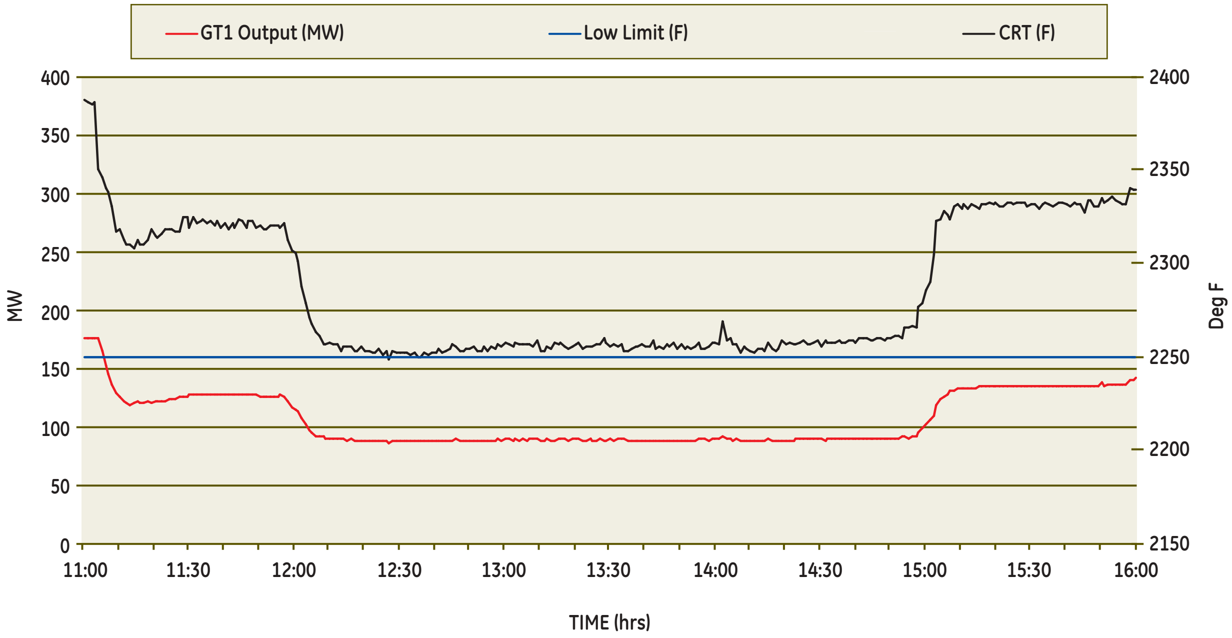

Figure 6 – **The CLOC system automatically prevents combustion reference temperature (CRT) from going below a minimum constraint. This ensures that allowable NO$_X$ emissions limits are not violated.**

parameters available to the operators are the selection of IGV angle control and the selection of inlet bleed heat. The combustion reference temperature signal is generated by a calculation in the DLN control software. This calculated temperature represents a reference for combustor mode sequencing and fuel split scheduling, but not unit load control. It should be noted that it is not a true indication of actual machine firing temperature, only a reference for firing mode sequencing. Only in a particular full-firing mode will the DLN system be fully operational. At a lower combustion reference temperature, the DLN will close certain fuel nozzles, resulting in elevated, out-of-compliance NO$_X$ levels.

As can be seen in Figures 6 and 7, the Combustion Reference Temperature (CRT) is closely related to the gross output of the combustion turbine. To prevent mode switching, it is imperative to maintain a minimum CRT when operating the machines. The CLOC system will lower output of the gas turbine generator, as dictated by a lower dispatch, until the combustion reference temperature reaches this lower limit. As with the minimum steam flow protection of the steam turbine, the CLOC system will first protect against constraint violations (in this case NO$_X$ levels) before attempting to minimize voluntary over-generation.

THE CLOC SYSTEM WILL FIRST PROTECT AGAINST CONSTRAINT VIOLATIONS BEFORE ATTEMPTING TO MINIMIZE VOLUNTARY OVER-GENERATION.

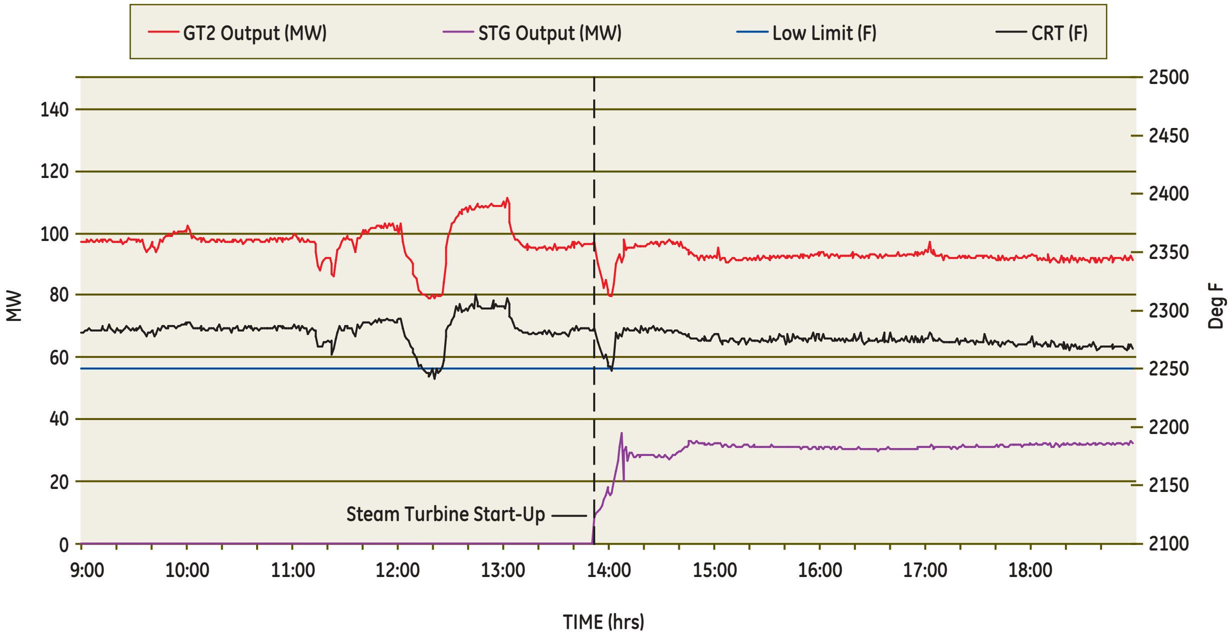

Figure 7 – **As the steam turbine starts up and begins delivering power, the output of the gas turbine is automatically ramped down to maintain net generation at dispatch. When Combustion Reference Temperature (CRT) reaches its lower limit, further gas turbine output reduction is stopped to prevent NO_x emissions violation.**

DEPENDENCE ON OPERATORS TO MONITOR AND ADJUST CLOC-CONTROLLED UNITS WHILE STARTING OR STOPPING ADDITIONAL ASSETS WAS ELIMINATED.

The right hand side of Figure 7 shows the effect of starting additional generating equipment (in this case, the steam turbine generator). CLOC automatically reduced output of the gas turbine generator to maintain net generation at dispatch. This reduction continued until the CRT reached its lower limit at which time the gas turbine stopped ramping down. It has been shown that this constraint control is very efficient in maintaining safe operating levels for the facility.

Operator Interactions – Starting and Stopping Assets

Dependence on operators to monitor and adjust CLOC-controlled units while starting or stopping additional assets was eliminated, because the CLOC system accounts for the net output of all generators, whether under system control or not, to ensure that dispatched generation is met accurately. This auto-adjust capability is conveyed in Figure 7, in addition to the constraint control that ensured minimum CRT was maintained.

Typically, dispatch schedules are entered for up to a week in advance by the dispatchers or by the plant operators using a Microsoft® Excel-based tool. Any dispatch change automatically triggers an alarm for the operator, and the change will not be accepted by the system unless the plant operator approves it. The use of a single database minimizes communication errors and provides a historical record for tracking purposes. The required verification by operators ensures that dispatchers do not allocate more than the plant can deliver and reduces the potential for errors based on incorrect schedule entries.

Current dispatch is transferred to the CLOC system exactly when needed. The system takes into account any ramp regulation that the plant may have with the grid owner. In WCE's case, the plant is only allowed to ramp to a different dispatch in the final five minutes of the current hour and the first five minutes of the next hour. Despite initiating a ramp in the final five minutes, the current hour's dispatch must be maintained. The CLOC system handles this constraint as well.

Figure 8 shows a 36-hour period in which the plant was dispatched. As indicated earlier, stopping an asset is easily accommodated by the CLOC system; the remaining operational assets were told automatically to make up the loss of generation and dispatch was met at the end of the period.

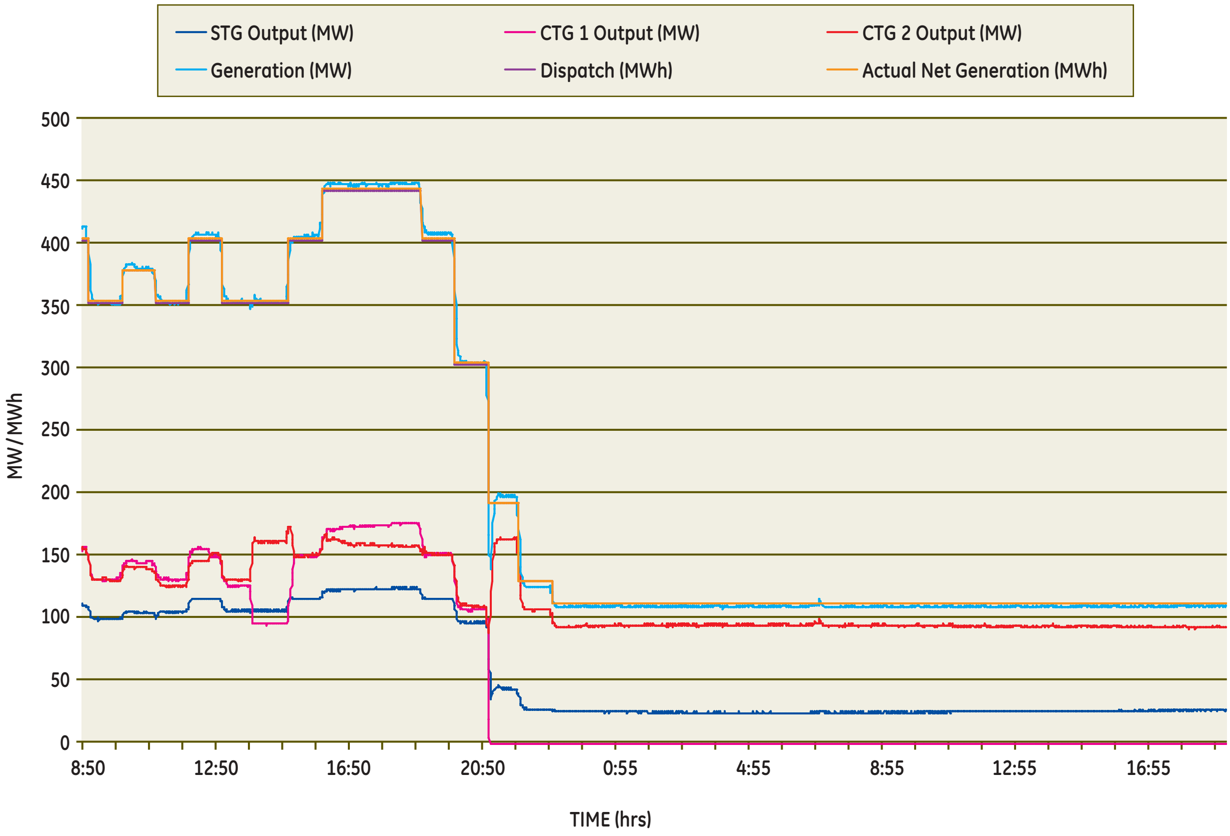

Figure 8 – **This 36-hour trend shows how the CLOC System automatically adjusts the output of each machine to maintain net generation at dispatch.**

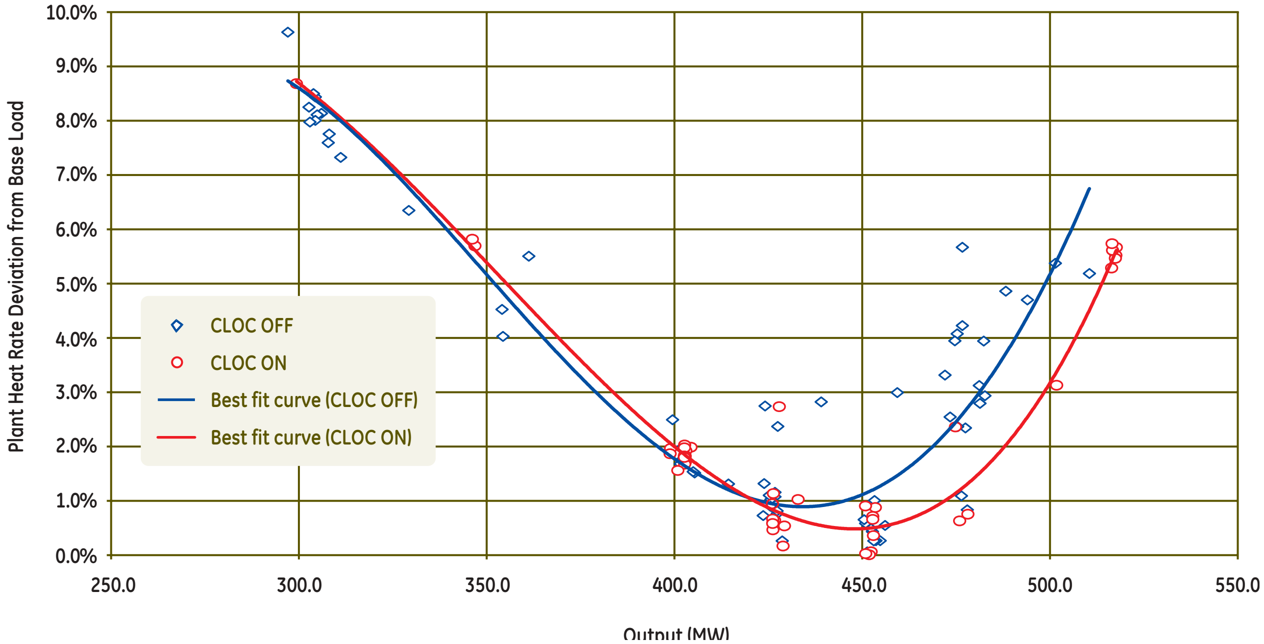

Figure 9 – **Heat Rate improvement achieved by the CLOC system when steam was not being exported. When fewer constraints are present, the optimization can manipulate variables with greater freedom, resulting in even better efficiency.**

Heat Rate Improvement

Figure 9 shows the heat rate of the facility, while under CLOC control, during a period in the summer of 2004 when the plant was not exporting steam. The optimizer becomes particularly effective at higher outputs, as can be seen from the two diverging heat rate curves. The upswing in heat rate at very high output is naturally caused by duct-firing. Figure 9 clearly indicates that if there are sufficient variables for the optimizer to manipulate, significant fuel savings can be achieved.

CLOSED-LOOP OPTIMIZATION CAN EASILY GENERATE RETURNS ON THE ORDER OF 700,000 TO 1.5MM USD PER YEAR.

Conclusion

Closed-loop control is able to address far more than just improvements in thermodynamic performance. As has been shown, GE's CLOC system was able to provide supervisory control that significantly outperformed basic regulatory control relying on manual setpoint changes. By introducing a hierarchy of control priorities, constraints such as maximum allowable NO_x emissions and minimum steam flow could be protected, voluntary over-generation could be lowered while preventing under-generation, and overall efficiency could be optimized. The use of closed-loop optimization was also shown to better maintain these benefits over time than open-loop strategies. For most plants, the combination of better generation control and closed-loop optimization can easily generate returns on the order of 700,000 to 1.5MM USD per year. O