An integrated Power Recovery Control System (PRCS) for a Power Recovery Train (PRT) provides automatic control during various operating modes: start-up, shut-down, full load, part load, and when either connected to or disconnected from an electrical grid. Additionally, PRCSs ensure high-speed adaptation to sudden mode-switches caused by component tripping or by loss of connection with electrical grids. Correspondingly, in the case of PRTs under normal operating conditions, recovered energy will (1) power a main air blower to supply combustion air to a regenerator, (2) generate electrical power for export, or (3) reduce power import. However, because of the inherent complexities of dual drivers (for example, steam turbines and hot-gas expanders), these trains are a challenge to operate and control; consequently PRTs, as a rule, are operated conservatively, thereby not maximizing their energy-recovery potential.

PRTs are common to industrial processes, such as Fluidized Catalytic Cracking Units (FCCU) in refineries, nitric acid sections of ammonia fertilizer plants, and other process plants. The sole purpose of these trains is to recover energy from a process regenerator’s flue gases and convert this kinetic/thermal energy into mechanical power; subsequently reducing the consumption of traditional energy sources.

Today's high cost of energy dictates that the energy in regeneration gases is salvaged and used to drive compressors, electric generators, and pumps. Compressor Controls Corporation (CCC) has developed and successfully implemented integrated PRCSs for several world-scale FCCUs in refineries around the globe. Figure 1 shows the following subsystems that comprise an integrated, multivariable PRCS:

- Integrated Turbomachinery Control System (ITCS)
- Regulatory Control System (RCS)
- Power Control System (PCS)

Accordingly, this article addresses: control system requisites for various operational modes; deficiencies inherent in conventional control systems; justification for an integrated PRCS; process simulation for system design; and field testing of machinery for algorithm configuration.
**TYPICAL PRT CONFIGURATIONS**

Figure 2 shows a typical PRT configuration: a hot-gas expander is connected to a main air blower (MAB), a steam turbine, and to either a synchronous or induction motor/generator set, all on one shaft. PRTs recover process energy by running hot flue-gas through the expander, which is designed to provide rated blower power. If excess power is available, motor/generator sets will export electric power.

**OPERATIONAL OBJECTIVES**

PRTs require precise, reliable control over a broad range of operating conditions to maximize FCCU availability and to realize energy efficiency; as a result, it is imperative that PRCSs meet the following regeneration cycle objectives.

- Provide sufficient airflow to the regenerator to (1) reactivate spent catalyst by burning off carbon deposits, (2) stabilize the fluidized bed, and (3) minimize CO yield by promoting its oxidation to CO₂.
- Maintain optimum differential pressure between the reactor and regenerator to regulate catalyst circulation and the catalyst/feed-oil ratio.
- Maximize energy recovery from the flue-gas stream.

CCC’s integrated PRCS provides varied functionality, size, and selectable fault tolerance to readily accommodate any PRT, in spite of process complexities, different PRT configurations, and types of FCCUs.

**CONVENTIONAL CONTROL SYSTEMS**

Conventional control systems used in PRTs exhibit certain deficiencies.

- Compressor antisurge control systems do not account for inlet condition changes brought on by ambient temperature variations, guide-vane geometry, and speed.
- Automatic, capacity/throughput control for MABs is given little consideration; in fact, some plants are built without this provision. As a result, MABs are operated at fixed throughput with operators frequently changing the guide-vane position or “adjusting the plant” to account for changes in ambient conditions and production demand. But even if automatic, capacity/throughput control exists, it is not integrated with antisurge control, and this renders the control system highly ineffective.
- No feedforward-response based, load-rejection/load-acceptance algorithms are implemented.
- PID control for speed regulation is ineffective for rapid suppression of imbalance in shaft power; for this reason, conventional control systems are inherently prone to overspeed trips in case of a breaker trip (Figure 6). To prevent overspeed, PRTs are operated inefficiently by using bypass valves to divert expander flow and to control reactor—regenerator (Rx—Rg) differential pressure. This action forces the expander to run with a partially opened inlet valve (operated in MANUAL mode); as a result, not maximizing power recovery. Additionally, FCCUs are subject to extreme excursions in variables around the Rx—Rg during such electrical upsets.

These significant deficiencies motivated CCC to design a PRCS that handled process and electrical upsets under all operating conditions.

**OPERATING MODES**

FCCUs are operated continuously for long periods, with the main goal of maximizing feed cracking. Occasionally, refineries are forced to operate production units at reduced rates because of machinery or process problems, downstream bottlenecks, upstream process-unit trips, seasonal factors, market economics, and feed availability. Established operating modes are described below.

- **Start-Up Mode**
  - Train start-up—Involves starting the steam turbine and putting the MAB in service. For configu-
The plant is subject to various operational modes. In some configurations, a standby air blower feeds air to the regenerator. Once the process is stabilized, energy from hot flue-gas powers the expander, which brings the MAB and the motor/generator set into service.

- **Process start-up** — The train connects to the electrical grid at a specified speed and the MAB is then brought on-line; subsequently, the Rx−Rg differential pressure and airflow to the regenerator are tightly controlled. The motor drives the MAB since the expander is unavailable.

- **Part Load Mode** — The plant is operated at reduced production rates, resulting in the MAB operating close to the surge-limit line. Generally, the process is unstable owing to loop interactions caused by the blowoff valve operating under antisurge control. Furthermore, motor power is gradually reduced as the expander becomes increasingly available, and interactions between the MAB and expander render the process difficult to control. Compressor Controls Corporation’s PRCS eliminates these controllability problems.

- **Base Load Mode** — The plant is operated at rates higher than its design parameters, with the goal to maximize production and power recovery, while operating within safe limits; that is, turbomachines are normally run at extremes, and excess power is exported to the electrical grid.

- **Breaker Trip Mode** — Depending on the plant load, PRTs can operate in either a motoring or a generating mode while synchronized with an electrical grid. In response to a breaker trip, the PRT transitions to a speed-governing mode wherein the steam turbine or the expander is used to control shaft speed. Such electrical interruptions cause significant process upsets and present major controllability challenges. Once the electrical fault is rectified, the train is reconnected to the grid.

- **Shutdown Mode** — The MAB is systematically unloaded during planned shutdowns, and it abruptly trips during emergency conditions.

### Overview of an Integrated PRCS

An integrated PRCS is essential for meeting FCCU production goals and, at the same time, for efficiently operating turbomachinery within a "safe zone of operation" (Figures 4 and 5), while maximizing power recovery. This is accomplished through integration of the MAB, turbine, motor/generator set, and reactor—regenerator controls.

Advanced control algorithms using adaptive open-loop and closed-loop techniques are required to prevent air blower surge and shaft overspeed trips. Multivariable, constraint control schemes are critical for maximizing power recovery without jeopardizing process requirements.

PRCSs must flexibly adapt to diverse turbomachinery train configurations (Figures 2 and 3): control algorithms should be executed in a maximum of 40 ms for an antisurge system, 40 ms for a reactor—regenerator system, and 20 ms for a governor (expander, steam turbine) system. The design should ensure fail-safe operation with built-in strategies that allow safe and reliable on-line operation upon failure of transmitter signals. A duplex, fault-tolerant, control architecture is recommended to increase system reliability and availability. Components of an integrated PRCS (Figure 1) are discussed below.

### Integrated Turbomachinery Control System (ITCS)

An ITCS is a multivariable, control system providing antisurge control and capacity/throughput control for the MAB, along with governor control for the expander and steam turbine.

**Antisurge Control System Requirements**

- **Algorithm invariance** — A surge-limit line, defined by an antisurge algorithm, must not vary with changing operating conditions. If the PRT’s speed varies, as in situations where the motor/generator set is not connected to the electrical grid, the MAB has a surge-limit surface instead of one curve. The parameters influencing these variations are guide-vane position, suction temperature, and operating speed. Antisurge algorithms must be energy efficient for all plant operating modes.

- **Constraint control** — An antisurge control system may be required to open the blowoff valve even while operating away from the surge limit. Piping or process constraints may require modulation of the blowoff valve to reduce discharge pressure at the MAB’s casing, thereby preventing structural damage, or to prevent upsets from the sudden opening of relief valves near the regenerator.

The algorithms should guarantee efficient blower operation within the safe zone of operation (Figure 4). Any opening of the blowoff valve initiates excessive power usage and reduces airflow to
the regenerator, which limits production. Clearly, an inefficient antisurge control system will result in production losses and excess power consumption.

**CAPACITY CONTROL SYSTEM REQUIREMENTS**

Accurate regulation of airflow to the regenerator is imperative for reasons cited earlier. A capacity control system’s primary function is to adjust flow rates in accordance with the regenerator’s combustion-air requirements. Variable guide vanes or stator vanes are generally used to regulate blower throughput; however, on rare occasions, blower speed may be varied to meet airflow requirements.

- **Main control variable**—The control variable is typically the mass flow of air to the regenerator. For regenerators employing parallel flow-valves, flow rates are maintained independently. Blower discharge pressure is adjusted to minimize throttling losses across valves; hence achieving Most Open Valve (MOV) control.

- **Constraint control**—Constraint control algorithms[^2] are required to limit turbomachinery operation within a safe zone of operation (Figures 4 and 5). An ITCS ensures that performance is optimized within this zone, allowing maximum throughput for the constraint. Process and/or equipment design constraints often require a capacity control system to limit throughput; thus preventing structural damage to machinery casings or driver overload.

- **Decoupling** with an antisurge control system—Antisurge and capacity control systems for the MAB must be integrated through dynamic decoupling. Regenerator pressure is a key factor influencing stability because a change in pressure alters the average density of the catalyst bed: depressurization can cause the bed to collapse, effecting a complete shutdown of the FCCU. For this reason, the antisurge controller’s action on the blowoff valve must be adapted to the strength of the process disturbance. Should the valve open excessively, airflow to the regenerator is sharply reduced; rapid opening of the blowoff valve only protects the machine, but it upsets the process. At the same time, unless decoupled, the performance controller may overcompensate for flow reduction causing unstable operation. Therefore, it is necessary to decouple the actions of the antisurge and capacity control systems.

- **Automated loading and unloading**—A steam-turbine starter accelerates the MAB to synchronous speed. Once the train is synchronized to the electrical grid, an operator can load the MAB either by manually operating the guide vanes, or by using the autoload sequences of the ITCS’s antisurge control and capacity control systems to regulate airflow to the regenerator. Successful manual loading depends on operator skill/experience; and it must be emphasized that even seemingly simple mistakes can prove costly and severe, causing delays of process start-up and possible damage from surge. In addition, quick opening/closing of the blowoff valve or fast changes in throughput can produce large swings in regenerator pressure, resulting in process shutdown and possible regenerator damage due to catalyst-bed collapse. Accordingly, it is important that the capacity control system implements automated, loading and unloading algorithms, where MAB throughput is integrated with the blowoff valve’s opening, to bring the blower on-line or take the blower off-line smoothly.
Governor Control Requirements

A governor system’s principal function is to maintain the balance of power between the driving and the driven equipment by regulating the power produced by active drivers. Conventional governor systems control the steam turbine and expander as independent units; however, the presence of multiple drivers on a shaft, as shown in Figure 2, presents significant challenges to the design of governor systems. And a high degree of coordination with an Rx–Rg control system is also required for optimal control and to maximize energy recovery.

Main control variable—An ITCS governor control system maintains train speed during start-up by throttling steam flow through a turbine’s steam inlet-valve. In some configurations (Figure 3), an expander may be used to bring the train to synchronous speed by throttling flue-gas flow through an inlet valve. For synchronization, the governor-speed set point is adjusted remotely by an autosynchronizing device.

After synchronization, the governor system operates in TRACKING mode (while steam flow to the turbine is controlled) and regains control if the breaker opens. High-speed data exchange with the Rx–Rg control system is constantly required in anticipation of electrical upsets to prevent pressure excursions in the regenerator during load rejection. Furthermore, the governor control system must maintain speed (using either the expander or steam turbine) on grid disconnect to avoid shaft overspeed.

When a breaker opens during electrical power generation, there is an instantaneous power imbalance, which contributes to machine acceleration. With conventional control systems, it is common for the PRT to trip on overspeed within seconds after a breaker opens (Figure 6).

Intelligent integrated control action between PRCS subsystems is required to maintain speed at a desired set point. Because of improved controllability, attributed to advanced control algorithms, the PRT can be better utilized without sacrificing plant reliability; this, in turn, leads to more efficient FCCU operation and a shorter payback period. Figure 7 shows major improvements in control system response (brought about by a PRCS) compared to conventional control systems. Speed and Rx–Rg ΔP excursions are minimized and overspeed trip is avoided.
Constraint control — A governor system must ensure that a steam turbine and expander operate within safe performance limits (Figure 5), while maximizing power recovery and maintaining the balance of power on the shaft. Typical constraints that must be taken into account in the design of governor control systems are (1) steam turbine, high wheel pressure; (2) minimum cooling, steam flow; (3) high exhaust temperature; (4) high exhaust flow; (5) turbine power limit; (6) maximum generation limit; and (7) maximum motoring limit.

**REGULATORY CONTROL SYSTEM (RCS)**

An RCS consists primarily of controls for the Rx—Rg to regulate regenerator flue gas by way of expander inlet/bypass valves. During part-load and start-up operations, an MAB’s blowoff valve is modulated by the antisurge control system. Therefore, it is imperative that inlet or bypass valves do not contend with the antisurge control system to cause compressor surge or choke. For this reason, integration between ITCS and the RCS becomes a significant factor.

Main Variable Control — An RCS’s primary function is maintaining differential pressure ($\Delta P$) across the Rx—Rg under all modes of operations, as described above in Operating Modes, Page 2. Once the expander has completed its warm-up cycle, and with sufficient availability of flue gas, the expander inlet valve regulates $\Delta P$. The bypass valve is kept closed, whenever possible, to maximize energy recovery.

Constraint Control and Breaker Disconnect — RCS must ensure that the regenerator is operated within a safe limit of the rated pressure, and its design must take into account means to isolate the expander from the process in the event of abnormal conditions. In case of dual driver configurations (Figure 2), RCS should make an intelligent selection between the expander or the steam turbine to regulate speed after breaker disconnect.

Another important function of an RCS is to calculate an open loop, feedforward response using a multivariable, predictive algorithm to overcome excursions in speed and $\Delta P$, owing to load rejection on breaker disconnect.

Automatic start-up sequence — Automatic start-up sequence brings a turbine or expander to rated speed following the machinery OEM’s schedules; it also considers: turbine thermal conditions to determine warm-up time and prevent damage from insufficient warm-up; minimizing operation in critical speed zones; and the handling of inadvertent operator errors.

Feedforward response must consider the amount of excess power to be
reduced from the drivers, and an equivalent amount of flue-gas flow to be diverted through the bypass valve to maintain regenerator pressure. The calculated load-rejection response and the decision of the active driver, in the event of breaker trip, should be integrated with the governor control system.

Integration of ITCS and RCS—An ITCS must limit motor/generator operation within safe operating limits. Excessive motoring, caused by MAB overload, is prevented by augmenting shaft power and by simultaneously constraining guide-vane opening to limit MAB capacity. In the case of excessive power generation, driver power is adjusted to operate at maximum permissible power without sacrificing Rx−Rg control; thus confirming the importance of ITCS and RCS integration.

**Power Control System (PCS)**

A PCS provides an autosynchronization function, electrical protection and safety, and Automatic Voltage Regulation (AVR) control for motor/generator sets.

- An autosync module interfaces with a governor control system to safely connect a generator to the electrical grid.
- A logic-and-sequencing module provides machinery protection in the form of over-and-under voltage/frequency conditions, motor overload trip, excessive winding temperature, and related electrical faults.
- An electrical protection module isolates the generator from the grid in the event of abnormal electrical conditions.
- An AVR control module regulates electrical elements in the field winding loop to control terminal voltage.

One may also encounter power control systems that regulate passive electrical elements to maintain a desired power factor of the load and reactive power generation. This subsystem is customized to the electrical equipment; it is typically supplied by the machine OEM and needs to be integrated with the ITCS.

**Advanced Control System**

An advanced control system runs in a traditional Distributed Control System (DCS) to optimize production. The function of an advanced control system is to generate set points to the ITCS and the RCS in response to the optimization routines employed in a DCS.

**Turbomachinery Performance Testing and Considerations for Simulation**

Surge-limit lines, to be configured in the antisurge control system, should be verified by testing (whenever possible) in the "as installed" condition to assure reliable antisurge control. For machine retrofits, original performance data (supplied by OEMs) usually deviates from actual data because of performance degradation and wear-and-tear of the machinery over time. Conducting MAB performance tests is the prerogative of the plant operator/owner and is determined from suggestions and requirements of the OEM, the control-system vendor, plant demand, and production.

The steam turbine and expander must also be field tested to determine their power and flow characteristics. Load rejection test data, at differing electrical loads, must be characterized to configure load-rejection/load-pickup algorithms.

Of the several PRCSs installed by CCC, a majority had the surge-limit line established by data collected through extensive field tests. Data from tests on steam turbines, expanders, and motor/generator sets was used to fine-tune the parameters (for algorithms) from values obtained during the design/engineering phase.

PRCS design for an FCCU is complex and challenging; therefore it is very important that all aspects of safety, reliability, and efficiency of the plant be considered during the design phase. Any oversight during this phase may prove costly and even catastrophic later during plant operation. Hence, it is highly recommended that PRCS in-the-loop simulation tests of the FCCU process (including turbomachines, regenerator, and reactor) be performed. “What if” scenarios, failure-mode analysis, and hazard-and-operability (HAZOP) studies should be conducted to ensure a fail-safe operation under all situations. The simulation system can later be used for factory acceptance tests and operator/maintenance training for plant personnel.

**Compressor Controls Corporation has developed and successfully implemented Integrated PRCSs for several world-scale FCCUs in refineries around the globe.**
Conclusion

After a process upset, large system time-constants will prevent the semi-automatic operation of PRTs from returning the process to maximum production levels at the first available opportunity. An automatic, integrated control system (such as a PRCS from Compressor Controls Corporation) increases the amount of energy recovered and decreases power consumption, while maximizing performance for each machine. This, then, translates into a boost in production, an increase in revenue, and a lowering of operating costs. Such a design results in smooth start-ups, a considerable decrease in downtimes, and prevents damage to rotating machines and equipment; in addition to providing high-quality control of machinery and of the process under normal and upset conditions.

Integration of control loops, feedforward responses, and information exchange between subsystems that comprise the PRCS permits an increase in the machinery’s operating envelope, while maintaining safety and reliability, thus maximizing production.

Although this article addresses the application of PRTs in an FCCU, the technology described is equally applicable to PRTs found in other processes.

REFERENCES


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