Taking control of a system

Nabil Abu-Khader, Compressor Controls Corp. (CCC), UAE, presents a number of operation scenarios for power recovery trains (PRTs).

Application software solutions called 'control applications' (or just 'controllers') can drive, protect and sequence entire power recovery trains (PRTs). In a PRT's integrated control system, speed, performance, expander and antisurge control applications run continuously to coordinate the control of the expander inlet and bypass valves in order to maintain the proper flow and pressure for a catalyst regeneration process. Excess energy developed by the system is applied to an electrical grid by way of a hot gas expander and generator.

Preliminaries

The method of calculating the mass flow rate in a pipe, W1, is typically governed by the relationship in equation 1:

$$W1 = C_W \cdot \sqrt{[\Delta P_o \cdot P_{fe}]/T_{fe}} \qquad (1)$$

Where:

- C_W is the mass flow scaling coefficient.
- ΔP_o is the differential pressure from the flow measuring device (in kPa for SI units, in WC for English units).
- P_{fe} is the pressure at the flow element in absolute units (kPaa for SI units, psia for English units).
- T_{fe} is the temperature at the flow element in absolute units (°K for SI units, °R for English units).

The generated frequency of an alternating current (AC) generator is typically governed by equation 2:

$$f = (N \cdot P)/120 \qquad (2)$$

Where:

- f is the frequency generated in Hz.
- N is the generator's speed in rpm.
- P is the number of magnetic poles.

Components of a PRT include the following:

- A hot gas expander (TK-50).
- An axial air blower (K-50).
- A steam turbine (ST) (TK-50A).
- A two-pole synchronous generator.
- A speed controller (SC-501).
- A steam flow controller (PRT-03).
- A performance air flow controller (FC-050) for the axial air blower.

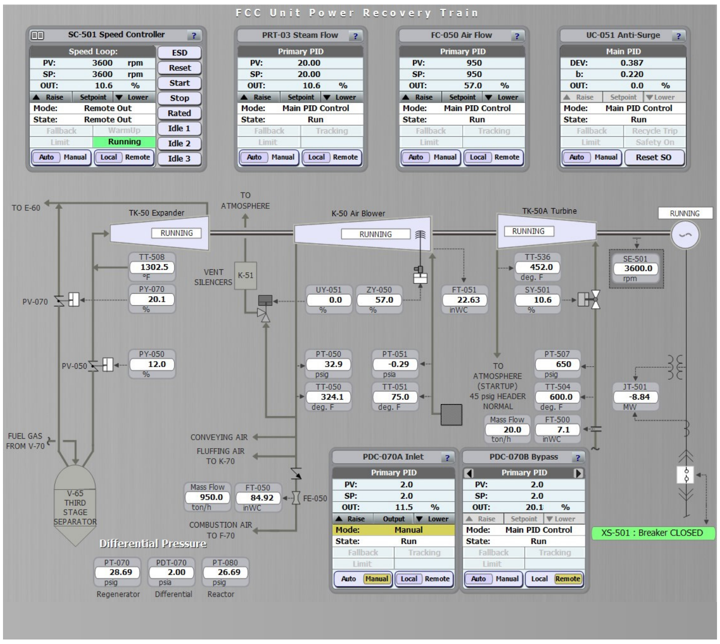
- An antisurge controller (UC-051), which positions the blow-off valve.
- A performance bypass controller (PDC-070B), which controls the bypass valve (PV-070) to assist the inlet valve controller in maintaining the proper delta-pressure between the reactor and regenerator.

Operation scenarios of a PRT for a fluidised bed catalytic cracking unit (FCCU)

Train start-up

PRT start-ups using an ST are performed using the speed control application's automatic start-up and warm-up sequences, avoiding critical speed ranges. This ramps up the turbine to the synchronous speed with the breaker open and no load. During this time, the expander control applications perform the following actions:

- The steam flow control application (which will control the turbine governor valve after the breaker is closed) tracks the output of the speed control application.
- The expander inlet valve control application holds the inlet valve closed, or at its configured start-up position.
- The expander bypass valve control application modulates the bypass valve to control the main process variable (delta pressure between the reactor and regenerator).



SC-501 Speed Controller – Speed Loop:
PV: 3600 rpm
SP: 3600 rpm
OUT: 10.6 %
Mode: Remote Out
State: Remote Out

PRT-03 Steam Flow – Primary PID
PV: 20.00
SP: 20.00
OUT: 10.6 %
Mode: Main PID Control
State: Run

FC-050 Air Flow – Primary PID
PV: 950
SP: 950
OUT: 57.0 %
Mode: Main PID Control
State: Run

UC-051 Anti-Surge – Main PID
DEV: 0.387
b: 0.220
OUT: 0.0 %
Mode: Main PID Control
State: Run

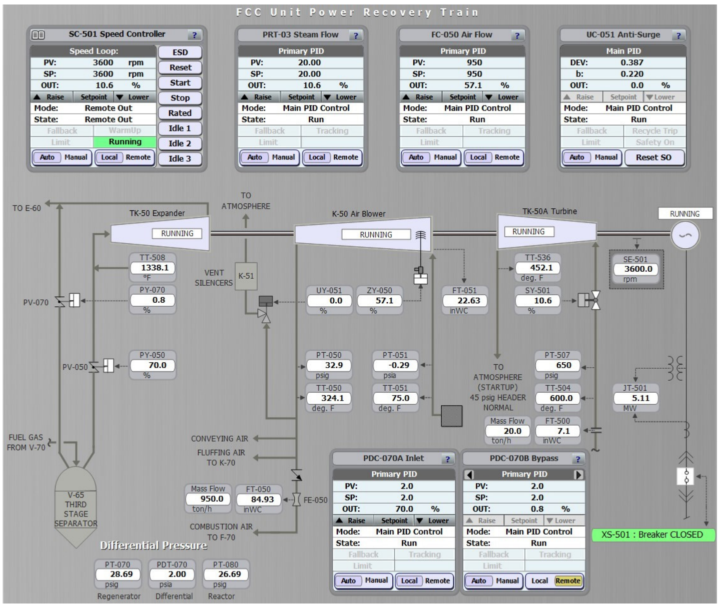
TT-508 1302.5 °F
PY-070 20.1 %
PY-050 12.0 %
UY-051 0.0 %
ZY-050 57.0 %
FT-051 22.63 inWC
TT-536 452.0 deg. F
SY-501 10.6 %
SE-501 3600.0 rpm
PT-050 32.9 psig
TT-050 324.1 deg. F
PT-051 -0.29 psia
TT-051 75.0 deg. F
PT-507 650 psig
TT-504 600.0 deg. F
Mass Flow 20.0 ton/h
FT-500 7.1 inWC
JT-501 -8.84 MW
Mass Flow 950.0 ton/h
FT-050 84.92 inWC
PT-070 28.69 psig
PDT-070 2.00 psia
PT-080 26.69 psig

PDC-070A Inlet – Primary PID
PV: 2.0
SP: 2.0
OUT: 11.5 %
Mode: Manual
State: Run

PDC-070B Bypass – Primary PID
PV: 2.0
SP: 2.0
OUT: 20.1 %
Mode: Main PID Control
State: Run

XS-501 : Breaker CLOSED

Figure 1. Motoring mode. Importing power is -8.84 MW.



SC-501 Speed Controller – Speed Loop:
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OUT: 10.6 %
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PRT-03 Steam Flow – Primary PID
PV: 20.00
SP: 20.00
OUT: 10.6 %
Mode: Main PID Control
State: Run

FC-050 Air Flow – Primary PID
PV: 950
SP: 950
OUT: 57.1 %
Mode: Main PID Control
State: Run

UC-051 Anti-Surge – Main PID
DEV: 0.387
b: 0.220
OUT: 0.0 %
Mode: Main PID Control
State: Run

TT-508 1338.1 °F
PY-070 0.8 %
PY-050 70.0 %
UY-051 0.0 %
ZY-050 57.1 %
FT-051 22.63 inWC
TT-536 452.1 deg. F
SY-501 10.6 %
SE-501 3600.0 rpm
PT-050 32.9 psig
TT-050 324.1 deg. F
PT-051 -0.29 psia
TT-051 75.0 deg. F
PT-507 650 psig
TT-504 600.0 deg. F
Mass Flow 20.0 ton/h
FT-500 7.1 inWC
JT-501 5.11 MW
Mass Flow 950.0 ton/h
FT-050 84.93 inWC
PT-070 28.69 psig
PDT-070 2.00 psia
PT-080 26.69 psig

PDC-070A Inlet – Primary PID
PV: 2.0
SP: 2.0
OUT: 70.0 %
Mode: Main PID Control
State: Run

PDC-070B Bypass – Primary PID
PV: 2.0
SP: 2.0
OUT: 0.8 %
Mode: Main PID Control
State: Run

XS-501 : Breaker CLOSED

Figure 2. Generating mode. Exporting power is 5.11 MW.

Once the 'Reset' command is asserted, and after meeting all start conditions, the speed controller will transfer to the 'ready' state. Once the 'start' command is asserted, the ST will start the PRT. Using the automatic turbine start-up sequence, the speed of the turbine will begin increasing to the synchronous speed of 3600 rpm. Since N = 3600 rpm and P = 2, then f = 60 Hz as per equation 2.

Closing the generator breaker and motoring mode

For the synchronisation of the generator with the electrical grid, an external auto synchronisation device is required to equalise the voltage, frequency, and phase angle prior to closing of the breaker.

When the breaker is closed to connect the generator to the electrical grid, the steam flow control application typically steps the governor valve open by a configurable amount to immediately place some load on the generator. Control of the turbine governor valve then switches from the speed to the steam flow control application, which maintains the flow of steam to the turbine blades. The air blower is also loaded to begin supplying compressed air to the reactor and regenerator. The performance control application controls the mass air flow to the air blower by modulating the inlet guide vanes (IGVs). The antisurge control application modulates the blow-off valve as necessary to protect the air blower from surge.

Once the turbine speed is within ±15 rpm of 3600 rpm, the generator breaker can be closed. As shown in Figure 1, closing the breaker will initiate the following actions:

- The steam flow controller (PRT-03) will begin controlling the turbine at 20 tph. It passes its output to the turbine governor valve through the speed controller (SC-501) using the 'Remote Out' functionality.
  - CW= 5.4, ΔPo = 7.1 in WC = 1.7667 Kpa, Pfe = 650 psig = 664.7 psia = 4582.9 Kpaa, and Tfe = 600 °F = 588.7 °K, then W1 = 20 tph as per equation 1.
- The speed controller (SC-501) will begin tracking the steam flow controller (PRT-03).
- The air flow controller (FC-050) will start up with a set point (SP) target of 950 tph, and its output will start ramping open the air blower IGVs.

  - CW = 238, ΔPo = 84.92 in WC = 21.12 Kpa, P_fe = 32.9 psig = 47.6 psia = 328.48 Kpaa, and Tfe = 324.1 °F = 435.4 °K, then W1 = 950 tph as per equation 1.
- The antisurge controller (UC-051) will begin ramping the blow-off valve closed.

Expander loading and generating mode

Once the air flow controller (FC-050) has reached its SP of 950 tph, the expander inlet controller (PDC-070A) can be switched to automatic with a delta-pressure SP of 2 psig between the reactor and regenerator. The expander inlet valve (PV-050) will start to open, and the bypass valve (PV-070) will start to close in order to maintain the pressure differential at 2 psig.

As shown in Figure 2, when the expander inlet controller is switched to automatic, the PRT will exit the motoring mode and begin the generating mode. At this point, 'sufficient' air flow is being supplied to the catalyst regenerator and the system is generating 5.11 MW of delivered power.

A forced motoring control feature prevents frequent switching between motoring and generation modes when the recovered and required powers are nearly equal.

Delivering more power

If more power is required, then the mass flow SP for the steam flow controller (PRT-03) can be increased. Frequency is maintained by the grid at 60 Hz.

This ST can produce more power than is required to drive the train. Therefore, in order to maximise power recovery, it is desirable to export power to the grid with the help of the ST.

Delivering less power

If less power is required, then closing the expander inlet valve (PV-050) will open the bypass valve (PV-070), which reduces the power to the grid. Frequency is maintained by the grid at 60 Hz.

Breaker trip while generating power with loadshedding algorithm enabled

If the electrical breaker trips during normal operation, the PRT control system will react quickly to either shed the excess power (to reduce the load on the train) if the PRT was generating power, or begin producing enough power to continue driving the train if the generator was motoring. The system will also begin controlling the speed of the train, which is no longer fixed by the grid frequency.

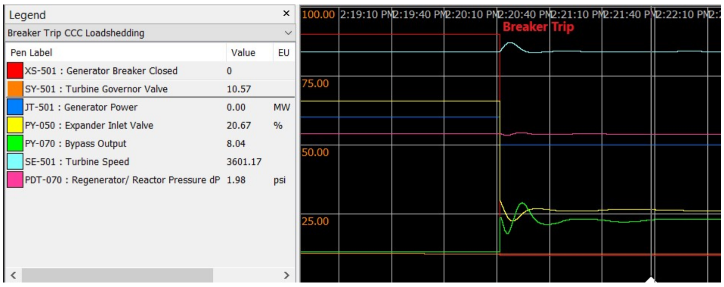
Let us return to the situation where the PRT was generating 5.11 MW (see the 'expander loading and generating mode' section of this article). As shown in Figure 3, during stable operation, if the breaker trips (red trend) then the expander inlet controller steps its valve (PV-050) down from 70% to around 21% (yellow trend), and the expander bypass controller steps its valve (PV-070) open from a nearly closed position (1%) to around 8% (green trend).

The speed of the turbine initially increases from 3600 rpm to around 3730 rpm (light blue trend), then begins to decrease. It was also noted that the expander inlet controller (PDC-070A) switched to its alternate PID loop (speed PID control) when the breaker tripped, and the speed controller started controlling the speed of the turbine by manipulating the inlet valve to the expander. Note that the turbine governor valve (SY-501) froze at 10.6% (orange trend).

The coordinated step actions of the expander inlet and bypass controllers (to shred excess power) have kept the speed of the turbine below the over speed trip (OST) level of 3800 rpm, and have maintained an adequate delta pressure between the reactor and regenerator.

Re-synching

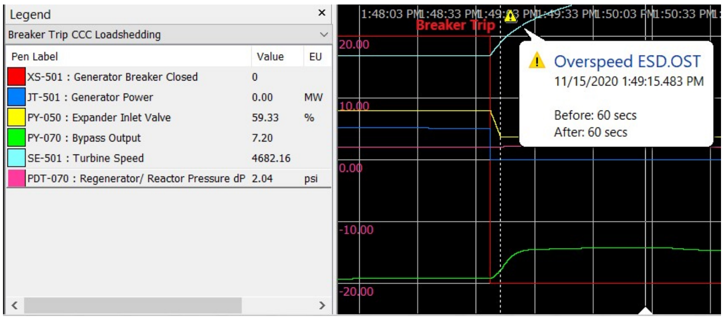
The speed of the turbine changed during the breaker trip, creating a situation where the speed of the expander and the turbine were out of sync. By initiating the 're-sync' command, the steam flow controller (PRT-03) will be idle, the inlet controller (PDC-070A) will switch to manual, and the speed controller (SC-501) will begin controlling the speed of the


Legend

Breaker Trip CCC Loadshedding

Pen Label	Value	EU
🟥 XS-501 : Generator Breaker Closed	0	
🟧 SY-501 : Turbine Governor Valve	10.57	
🟦 JT-501 : Generator Power	0.00	MW
🟨 PY-050 : Expander Inlet Valve	20.67	%
🟩 PY-070 : Bypass Output	8.04	
🟦 SE-501 : Turbine Speed	3601.17	
🟪 PDT-070 : Regenerator/ Reactor Pressure dP	1.98	psi

Figure 3. System response for a breaker trip while loadshedding algorithm is enabled.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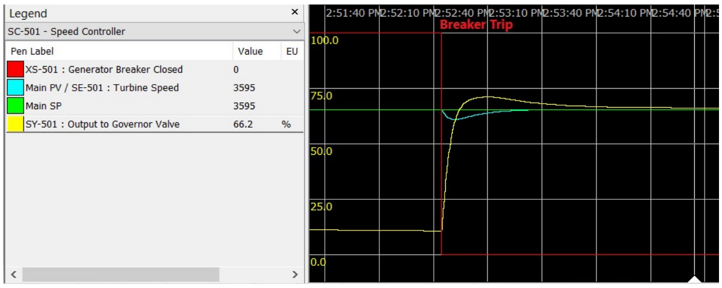
Breaker Trip CCC Loadshedding

Pen Label	Value	EU
🟥 XS-501 : Generator Breaker Closed	0	
🟦 JT-501 : Generator Power	0.00	MW
🟨 PY-050 : Expander Inlet Valve	59.33	%
🟩 PY-070 : Bypass Output	7.20	
🟦 SE-501 : Turbine Speed	4682.16	
🟪 PDT-070 : Regenerator/ Reactor Pressure dP	2.04	psi

⚠ Overspeed ESD.OST
11/15/2020 1:49:15.483 PM

Before: 60 secs
After: 60 secs

Figure 4. System response for a breaker trip while loadshedding algorithm is disabled.


Legend

SC-501 - Speed Controller

Pen Label	Value	EU
🟥 XS-501 : Generator Breaker Closed	0	
🟦 Main PV / SE-501 : Turbine Speed	3595	
🟩 Main SP	3595	
🟨 SY-501 : Output to Governor Valve	66.2	%

Figure 5. System response for a breaker trip while in motoring mode.

turbine. If necessary, the speed controller SP can be manually set back to 3600 rpm to match the grid frequency of 60 Hz. Once the turbine speed is within ±5 rpm of 3600 rpm, the generator breaker can be closed again. Switching the expander inlet controller back to automatic with a delta pressure SP of 2 psig between the reactor and regenerator will slowly re-establish the power generation of 5.11 MW, as was shown before.

Breaker trip while generating power with loadshedding algorithm disabled

During stable operation, which is the moment in which the breaker trips with the loadshedding algorithm disabled, the speed of the turbine increases rapidly. The PID control loops within the expander inlet and bypass controllers react independently, trying to control the situation. As shown in Figure 4, the inlet controller reduces its output (yellow trend) while the bypass controller increases its output (green trend). However, the PID actions of these controllers were not enough to prevent the speed of the turbine from reaching the OST limit of 3800 rpm, triggering an emergency shutdown (ESD) for the ST.

Breaker trip while in motoring mode

Let us return to the situation where the PRT was running in motoring mode (see the ‘closing the generator breaker and motoring mode’ section). As shown in Figure 5, if the breaker trips (red trend) while the generator is motoring, the PRT control system quickly steps the turbine governor valve (SY-501) open from 10.6% to 66.2% (yellow trend) in order to produce more power and continue driving the PRT.

Train shutdown

A normal shutdown can be initiated by asserting the ‘stop’ command. The expander inlet valve (PV-050) will begin to close at a configured rate, and the expander bypass valve (PV-070) will begin controlling the process variable. The train will shut down gradually as per the configured shutdown sequence.

If an ESD is triggered, the output of the speed controller (SC-501), the steam flow controller (PRT-03), the air flow controller (FC-050), the inlet controller (PDC-070A), and the bypass controller (PDC-070B) drop to zero, and the antisurge controller (UC-051) fully opens the blow-off valve.

Conclusion

This article has demonstrated that an integrated control system can safely run a PRT by utilising the loadshedding algorithm in case of a breaker trip. The control system also maintains a proper flow and pressure for a catalyst regeneration process under different conditions. Synchronising actions among different controllers is essential to maintaining grid stability. Other advanced control features, such as loop decoupling, also play a crucial role to eliminate cyclic interactions between different controller applications.

References

1. UM6413 and UM5525 Reference Manuals, Compressor Controls Corp., (March 2019).
2. ABU-KHADER, N., 'Process Recovery Train Controls', *Turbomachinery International Magazine*, (Nov/Dec 2021).