AN EMPIRICAL SOLUTION TO AN ANTI-SURGE CONTROL PROBLEM

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ABSTRACT

Steps taken by a du Pont team to prevent surge in a 23,000 hp process air compressor are reviewed. The process has several reactors which must interlock down quickly for safety reasons. These interlocks can occur on one, several, or all reactors, simultaneously. During large upsets, the original control scheme could not prevent surge, which then caused shutdown of the entire system.

Several constraints complicated the solution. To protect the axial compressor casing from excessive blade stresses, the compressor has to be interlocked on surge. The control margin between the surge control and actual surge line has to be small to conserve energy and improve turndown. A second control margin was required to feed any excess air to be fed to an energy recovery expander.

The improved control scheme uses a dual-gain controller which shifts to high gain during upsets. High speed recording equipment was used to track process variables, control signals and actual valve position. This information was then used along with computer simulations to tune controllers and control valve boosters.

INTRODUCTION

A 23,300 horsepower (hp) synchronous motor-gear driven process air compressor with a waste gas expander is shown in Figure 1. Particular care was taken on design "front-end loading" to ensure high reliability in service. The startup went well. Goals were met on timing, safety, capacity and energy savings, and the machine ran smooth mechanically. After about six months of operation, however, it became apparent that the surge control system design was not adequate. Each time the compressor surged, the entire process would stop, costing more money and casting shadows on an otherwise good running machine.

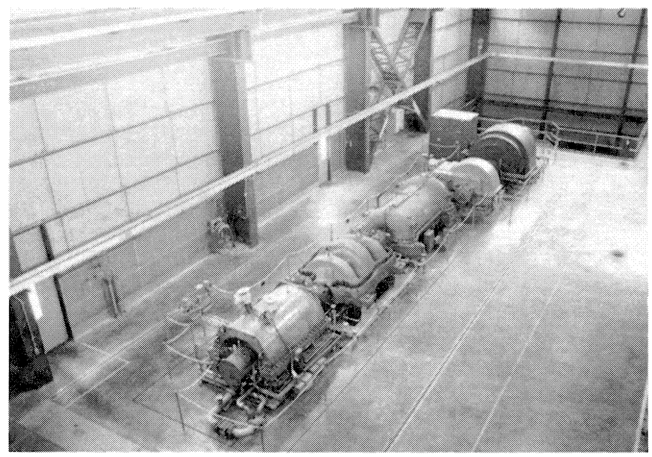

Figure 1. Compression Train. Shown (front to rear): expander, the high pressure case, low pressure case, speed increaser and synchronous motor.

The low pressure case (LPC) is a 14-stage axial compressor with variable stator vanes, followed by an intercooler. This feeds the high pressure case (HPC), which is a seven-stage centrifugal compressor with a second intercooler. Air at 385 psig is fed to the process along with air from another centrifugal compressor. Waste gas from the process is used to drive the expander, which assists the motor.

A number of design audits were carried out including:

- Lateral rotor response
- Torsional rotor response
- Synchronous motor transient torsional excitation
- Foundation analysis
- Blade vibration modal analysis for the axial compressor and the expander
- Computer simulation of the interaction between the process controls.

Field verification of many aspects of these audits was carried out at startup. In all areas, these audits improved the designs prior to fabrication. The train performed well in nearly all respects, except for surge control.

The efforts to solve the problem are presented herein. The objectives were to:

- Keep the compressor out of surge
- Keep the process online
- Avoid sacrificing energy savings.

To accomplish this, the program was to:

- Identify circumstances leading to surge
- Consider alternate solutions
- Implement the most practical ones, (with minimum interruption to plant operation).

CONTROL STRATEGY

A simplified control strategy for the compressor and expander is shown on Figure 2. These control loops are:

- Stator vane pressure control
- Low pressure case anti-surge vent flow control
- High pressure case anti-surge vent flow control
- Excess air spillback control
- Waste gas backpressure control.

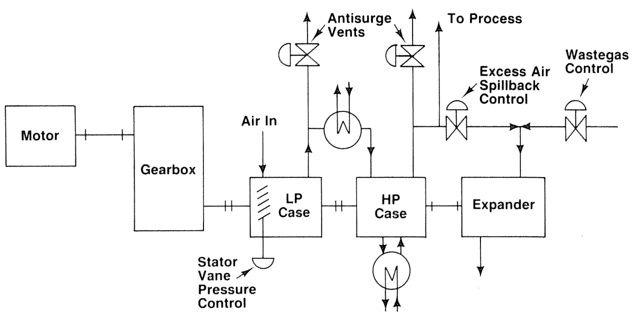

Figure 2. Compressor and Expander Control Loops.

Not shown on the diagram in Figure 2 are a number of process loops which have the potential of interacting with these controls and causing process upsets. All of the controls use four to twenty milliamp signals. These are converted to one to five volt signals at the instruments.

Variable stator blades are used in the axial compressor to provide turndown, since machine speed is fixed. They are used to control the pressure of the compressor.

Anti-surge valves are provided on both casings of the compressor. Air from each of the compressors feeds a common air header and is then flow controlled into each reactor. Process waste gas is fed to the expander by backpressure control.

In addition to these valves (shown on Figure 2), the other compressor has an anti-surge valve, and there are several valves on each reactor. All together, thirty-one flow and pressure controllers were modelled. One of the goals of the digital computer simulation was to help select controller tuning constants to prevent all these controls from interacting with each other. Another important goal was to ensure that the anti-surge controls were fast enough. Controllers were modelled with inputs for proportional, integral, deadband and signal "noise" in a few cases. Tank and pipe volumes as well as compressor head curves were input.

The controls for the HPC anti-surge valve are a little more complex than a standard proportional plus integral controller (Figure 3). A function generator is used to create an anti-surge control line parallel to the actual surge line (Figure 4). Pressure is the input and the required flow output is the setpoint for the controller. The valve is set to be failsafe, so that on loss of control voltage or instrument air, the anti-surge valve will fail open. Output from the controller is first compared to an override signal based on pressure (Figure 5). If the pressure is too high, a signal is produced which will be lower than controller output and the anti-surge valve will begin to open. When pressure reaches the top of the override range, the signal will completely open the anti-surge valve. The high

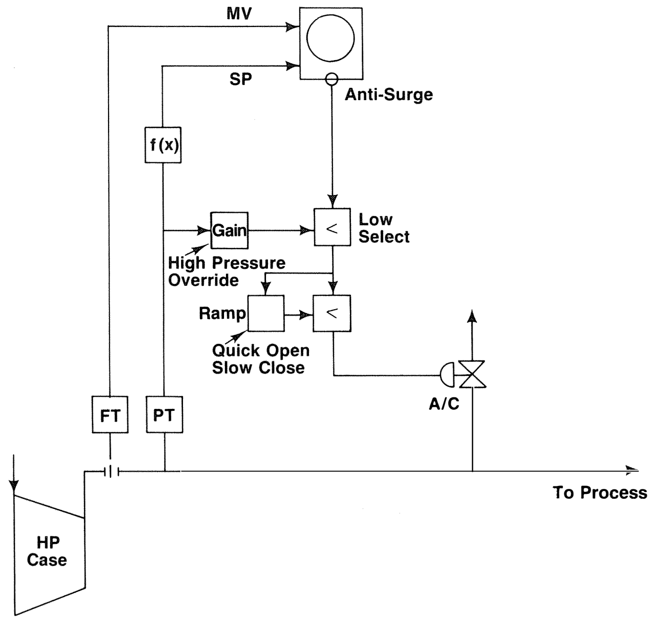

Figure 3. Initial Anti-Surge Loop. MV = Measured Variable, SP = Setpoint, FT = Flow Transmitter, PT = Pressure Transmitter, f(x) = Function Generator, A/C = Air to Close.

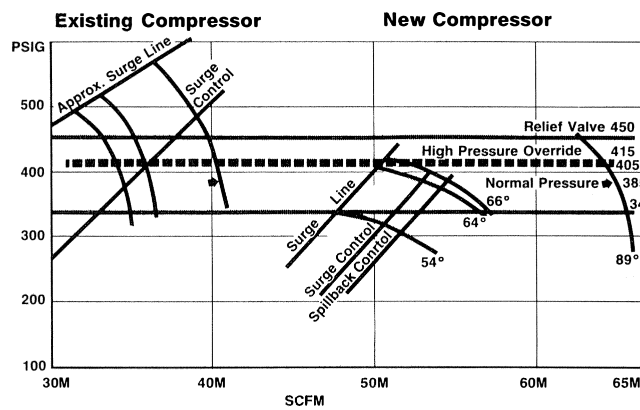

Figure 4. Characteristic Head Curve for Each Compressor. Note that the new compressor head curves are much flatter at minimum flow than the existing compressor.

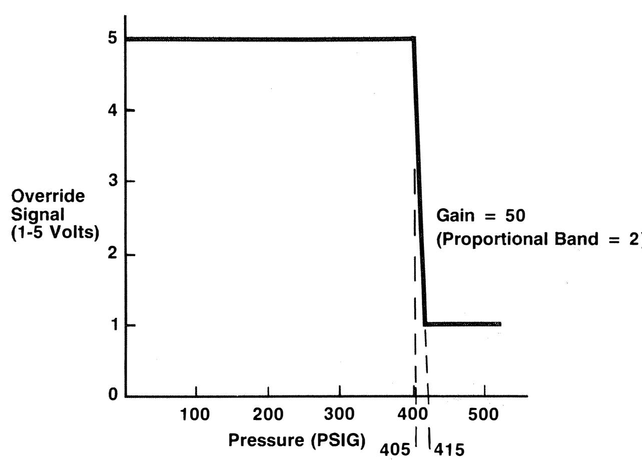

Figure 5. High Pressure Override. When the pressure becomes too high, this signal overrides the signal from the flow controller through a low signal select.

pressure override is pure gain, with no integral or derivative action. As soon as the pressure is restored, the signal ceases. Its main purpose is to help the process, although it can also help prevent surge.

This compressor train is equipped with an expander for energy recovery, and normally uses only waste gass. However, when the plant is using less air than the compressor needs to stay out of surge, the excess air can be routed back to the expander to recover energy. To accomplish this, the spillback controller setpoint is biased slightly above the anti-surge setpoint (Figures 4 and 6). The anti-surge controller is tuned to be quick reacting. The spillback controller is significantly slower to prevent interaction, since they are in competition for the same flow.

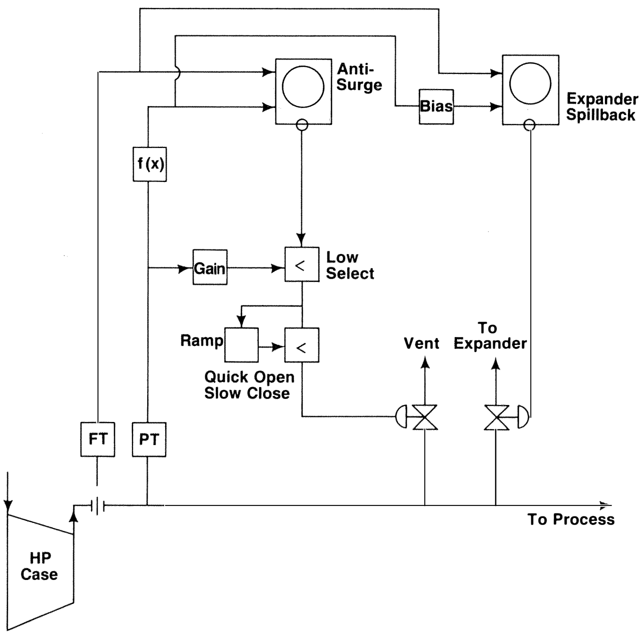

Figure 6. Expander Spillback Loop Added to Anti-Surge Loop. Both control the same flow and have potential for interaction. Spillback allows any excess air to be routed to the expander rather than vent.

The HPC anti-surge valve is actually expected to perform two very different functions. When process reactors shut down, the anti-surge valve is intended to respond quickly and vent to the atmosphere. Typically, this must occur in a matter of a few seconds and requires very fast tuning, similar to the high pressure override. Once the HPC anti-surge valve and process have stabilized, the air must transfer more slowly from the anti-surge valve to the spillback valve, which goes to the expander.

ISOLATION OF THE PROBLEM

In the first five months of operation, the compressor shut down five times, due to surge. The events leading up to surge and shutdown were quite fast, typically happening in a matter of a few seconds. Thus, stripchart data and "first out" alarm systems were generally inadequate to explain the real sequence of events. Several problems were found each time which seemed to explain the events, and masked the real problem. Among these were sticky valve operation and some minor errors in controller calibration. The high pressure override had been observed to function in a number of plant upsets and kept the compressor from surging.

In the sixth month of operation, the compressor went down on surge four times. The plant was running at lower rates, so in each case the compressor was already at minimum flow before surge occurred. The computer simulation showed that the override should keep the machine out of surge, yet the stripchart records indicated that the pressure never got high enough to reach the override in any of the four cases.

A comparison of the two compressors depicted on Figure 4 shows that at maximum flows, the head curves have similar slopes. However, at minimum flows, the new machine head curve is nearly flat, while the existing machine has little change. These actual head curves of the new machine turned out to be somewhat flatter than predicted by the manufacturer. Further, note that the 66° blade angle curve just reaches the top of the high pressure override range when it also meets the actual surge line. The override can only put out a full signal when the pressure is at the top of the range. Maximum valve stroke speed is only reached if the valve receives full controller output signal. Thus, maximum valve speed could not be attained when the compressor was operating at minimum flow, until the compressor was actually surging. By comparison, the existing compressor with steeper head curves would receive a full controller output signal long before reaching the surge line. The plant had never experienced problems with the existing compressor going into surge.

ALTERNATIVES AND CONSTRAINTS

A team was formed to investigate the surge problem more thoroughly and implement solutions. Several of the many alternatives considered were:

- Slow the process interlocks
- Allow the compressor to surge more than once
- Increase the control margin from the surge line
- Increase gain on the existing controller
- Use a low flow override.

One of the first proposals to solve the surge problem was to slow the reactor shutdown. This would be done by slowing the closing time on the reactor air feed valves. However, this proved to be impossible since there are several constraints on pressure control.

The process has an explosive range, so each reactor must be able to interlock offline quickly. If the air supply header pressure becomes too low, the reactor valves must be able to interlock closed quickly to prevent backflow of process material. Several other events including loss of one air compressor can also call for rapid shutdown of the reactors. They can shut down in various combinations, including all at once. In addition to the low air header pressure interlock, air header pressure which is too high can be bad. When one reactor goes down, the header pressure rises. Unless pressure is limited, more air is forced into the remaining reactors and drives them toward the explosive region. This can cause them to interlock, also causing a domino effect. This was the original purpose of the high pressure override.

Another proposal was to permit the compressor to go through more than one surge cycle before interlocking. This was rejected for two reasons. First, the entire process still goes down. Second, after axial blade stresses were measured on several stator blades during startup, it was found that blade stresses were quite high during surge. The manufacturer agreed that the machine should be shutdown on the first surge cycle.

A third proposal was to move the surge control line further away from the surge line. This was done as a short term solution, but was undesirable on a long term basis, because of the increased energy costs.

Increasing the gain on the existing controller was also proposed. However, experience with the tuning during startup had shown that gain could not be increased much without affecting stability. Yet, a much higher gain was being used successfully on the high pressure override. There were several reasons for the stability of the high pressure override:

- No integral (reset)
- Asymmetric/normally inactive
- Different function than proportional/integral control.

The integral (or reset) action is continually integrating controller offset over time and adding to the controller signal. The integral signal is by nature a destabilizing input, and it becomes a matter of how much the control loop can stand. By all indications, the HPC anti-surge controller was at its limit. In contrast, an override is pure gain and has no integral action. Secondly, the high pressure override is asymmetric which helps to break up cycles [1], is only to open the valve, not close it. Though the gain of 50 is quite high, it is normally inactive. Finally, anti-surge controls were expected to perform two very different functions. The first was to smoothly transfer any excess air to the expander spillback, using proportional and integral controls. The second was to respond quickly to process shutdown. The high pressure override could provide that quick response at high flows, but not at the minimum flow, since the pressure changes very little. A low flow override was needed.

All of these constraints pointed in the same direction. It is not enough to just save the compressor from surge. For successful operation, the compressor has to stay within the limits shown on Figure 4. If the valve reacts too slowly, the compressor can surge, or the process can be interlocked by too much air in the remaining reactors. If the valve opens too far or too long, the process can be interlocked on low header pressure. The goal was to handle any number of reactor interlocks without allowing more interlocks.

TESTING PROGRAM

As is common in troubleshooting, there is usually insufficient data available to decide what really happened. Stripchart data and 15 seconds of computer data were already available for most of the critical variables. Neither source of data was able to catch the rapid transient conditions leading to the shutdown of the process and the compressor. The following program was proposed:

- Investigate methods of providing a low flow override
- Tape record critical variables
- Simulate controls responses with false inputs
- Test the compressor off-line/on-line.

A 14 channel tape recorder was used to monitor the control signals, transmitter signals and other critical variables. The actual position of the anti-surge valve was considered critical not only because of anticipated system time lags, but also because of an early history of sticky valve operation. The valve position was measured by use of a wire potentiometer.

After recording the data on tape, signals of interest were played back to a high speed stripchart recorder. It was then possible to see the sequence of events for the first time.

CONTROLLER/VALVE RESPONSE TESTS

Testing began by applying full scale step input signals directly to the valves, to check maximum stroking speeds (Figure 7). This method checked most of the other valves in the system. In several cases, positioner springs were rubbing against string guards and causing erratic motion. Errors in the calibration were also detectable.

False signals were fed into the pressure and the flow transmitters to simulate upset (Figure 4). The pressure was set

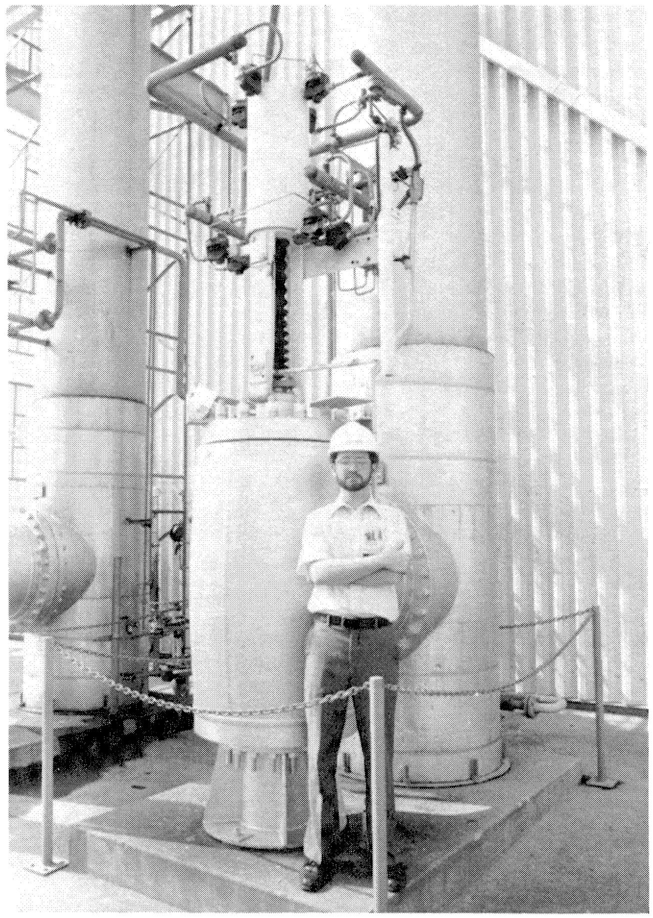

Figure 7. High Pressure Case Anti-Surge Valve.

at 385 psig and flow was set at the minimum control line. The pressure requires a flow for the controller set point. The false pressure was then quickly increased to 415 psig. As expected, the valve opened completely in less than two seconds, due to the action of the high pressure override.

Conditions were restored to 385 psig and minimum flow once again. The false flow signal was quickly decreased to the surge line, a seven percent offset on the controller. The valve took nearly two minutes to open, clearly demonstrating that the proportional and integral part of the controls could not keep the compressor out of surge. That agrees with calculated opening time:

$$\begin{aligned}\text{Output Percent} &= 100\,[G + \frac{G}{R}(t)\,]\,\text{err}\\ &= 100\,[0.8 + \frac{0.8}{0.12}(2)\,]\,0.07\\ &= 100 \text{ percent}\end{aligned} \qquad (1)$$

where: $G = \text{gain} = \dfrac{100}{\text{proportional band}} = \dfrac{100}{120} = 0.8$

$R = \text{reset} = 0.12$ minutes/repeat

$t = \text{time in minutes} = 2$ *minutes*

$\text{err} = \text{error} = \text{setpoint} - \text{measured} = 0.07 = 7$ percent

DUAL GAIN CONTROLLER

The controls vendor considered the needs and suggested a dual gain controller, which could accomplish nearly the same things as a pure gain low flow override. The advantages of this type of controller were:

- Control card was an on-the-shelf item.
- Control card was interchangeable with the existing card,

with no wiring changes required.

- Controller configuration was very flexible.

The disadvantage of the controller was that:

- One integral (reset) setting applies to both the high and low gain settings. Thus, the low flow override would not be strictly a pure gain signal, and could introduce some cycling, which might upset the process.

The configuration of the controller is quite flexible (Figure 8). The controller can be set in the deviation mode, which means the breakpoints track the setpoint instead of being fixed values. This is valuable since the surge control line is sloped. The breakpoints can be set independently on either side of the setpoint when the controller shifts from low to high gain. For this particular controller, the low breakpoint is set about two percent below setpoint and the high breakpoint is set at five volts, which is outside of the useful controller range. High gain for closing the valve was not desirable.

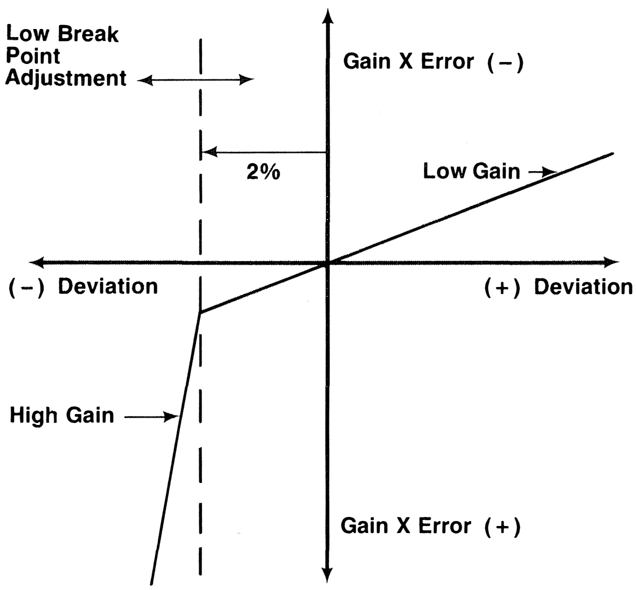

Figure 8. Dual Gain Controller Settings. Low breakpoint is set two percent below setpoint, and will track the setpoint as it moves. Low gain is 0.66 (proportional band = 150) and high gain is 25 (proportional band = 4).

Based on the performance of the high pressure override, a gain of 25 (four percent proportional band) was selected for the high gain portion of the controller. It was decided, based on computer simulations, to reduce the gain used for the high pressure override. The controller also has a reset function, whereas the high pressure override has no reset. The low gain was set at 0.66 (150 percent proportional band). Given these values, the controller output was expected to be:

$$\begin{aligned}\text{Output percent} &= 100\,[G + \frac{G}{R}(t)\,]\,\text{err} \\ &= 100\,[25 + \frac{25}{3}(0)\,]\,0.04 \\ &= 100 \qquad (2)\end{aligned}$$

where: G = 25
R = 3 seconds/reset
t = 0 seconds
err = 0.04 = 4 percent

With a smaller controller flow offset, it would now be possible to send a full signal to the valve and open it at the maximum speed before the flow drops to the surge line, which is seven percent away (Figure 9).

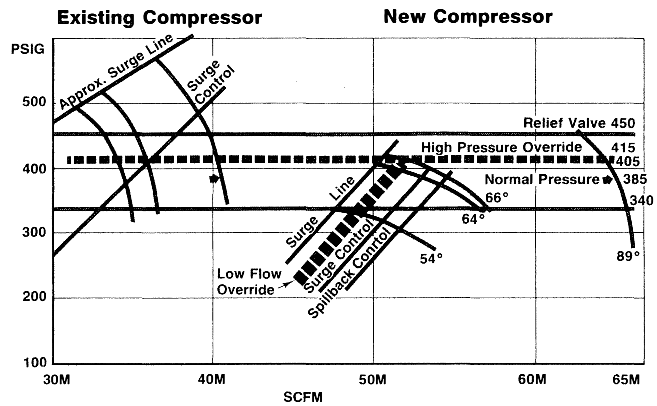

Figure 9. Characteristic Head Curve with the Low Flow Override Added.

The dual gain control scheme was simulated, with false signals as before, to verify that the hardware would perform as expected. After checkout was complete, the compressor was started, but not put online with the process. All compressor discharge air was spilled to the expander. Sudden upsets in the plant were simulated by making sudden changes utilizing the spillback air valve. Data from the upsets was recorded and displayed on high speed stripchart recorders.

Availability of high resolution data made two points apparent: 1) The stator vanes were closing too quickly and lowering the performance of the compressor (Figure 9). This reduced the flow and moved the operating point away from the high pressure override. The stator vane gain was, therefore, reducd from 1.0 to 0.33 (proportional band changed from 100 percent to 300 percent). The ramp function card also had the tendency to follow the flow fluctuations. This closed the deliberate offset between the anti-surge and spillback lines, and made transfer of air to spillback a very long process. To prevent this, the ramp card was changed to a lag card which averaged flow fluctuations (Figure 10). The compressor was valved into the plant after satisfactory simulations were made, using the spillback valve. The next series of tests was conducted by deliberately shutting down reactors and monitoring the responses.

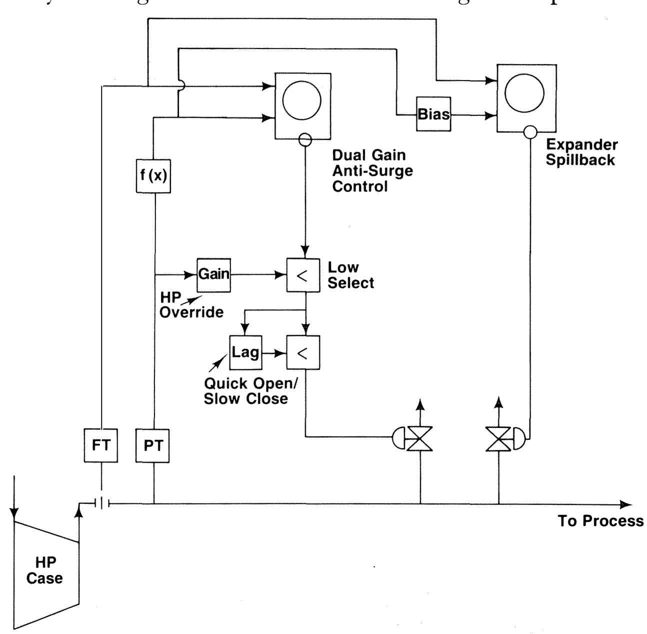

Figure 10. Modifications to the Control Scheme. A dual gain controller and a lag card (in place of the ramp card) were installed.

Once the plant reached steady state operation, one reactor was interlocked. A small decrease in flow occurred almost immediately (Figure 11). However, it was nearly ten seconds before flow dropped enough to affect the control signal. Note that the anti-surge control line was set below the spillback control line (Figure 9). Until flow drops to the control line, there is no change in the anti-surge control signal. Once the flow in the HPC dropped two percent below the flow control line, the controller high gain system reacted and quickly opened the anti-surge valve.

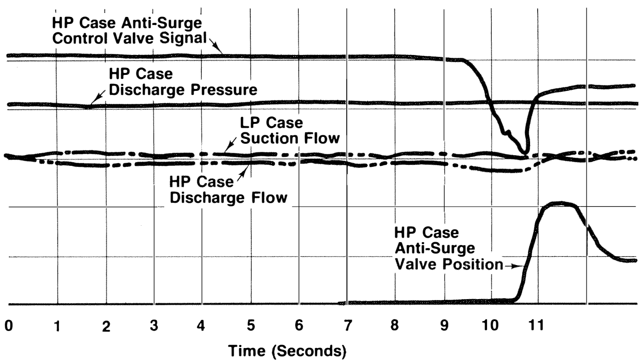

Figure 11. Single Reactor Shutdown—System Response.

The next plant test was shutting down two reactors simultaneously (Figure 12). The flow dropped for about 2½ sec before the controllers began dropping the signal in low gain mode. The high gain feature was activated 0.4 sec later. Even though the valve opened 62 percent in just one second, it lagged behind the control signal by about 0.5 sec. Identifying this behavior would not have been possible without measuring the actual valve position. It should also be noted that the discharge pressure from the HPC increased very slightly.

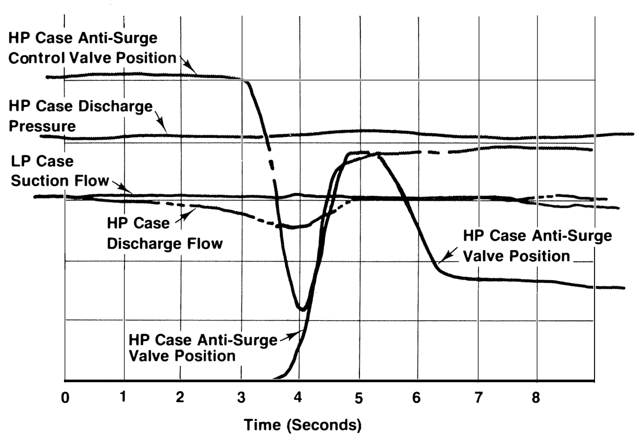

Figure 12. Two Reactor Shutdown—System Response.

The final test was shutting down all three of the reactors. The flow dropped for only 0.8 sec before the high gain reacted (Figure 13). However, the control signal was just reaching its full output 0.6 sec later when the HPC surged. The HPC anti-surge valve had only opened about ten percent. After one second more, the LPC surged and shut the compressor down. Meanwhile, the HPC anti-surge valve was just reaching its full opened position. The anti-surge valve stayed open, since that is the shutdown position. The high speed data recording showed how quickly big upsets can occur. Valve motion again lagged the control signal by about 0.4 sec.

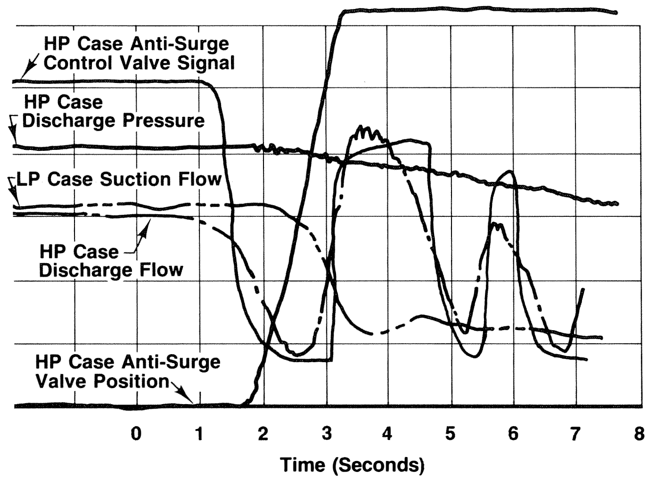

Figure 13. Three Reactor Shutdown—System Response. Compressor surged and was shut down.

The rapid fluctuations in the HPC pressure are incipient surge, or the surging of a single stage. The mean HPC discharge pressure only increased about 3 psi when the compressor surged. The compressor manufacturer's performance map showed it should have increased about 20 psi. The air residence time in each intercooler is about four seconds, or roughly eight seconds for the whole machine (Figure 14). The surge cycle is much faster. The compressor is actually in a transient mode, whereas the performance map represents steady state conditions.

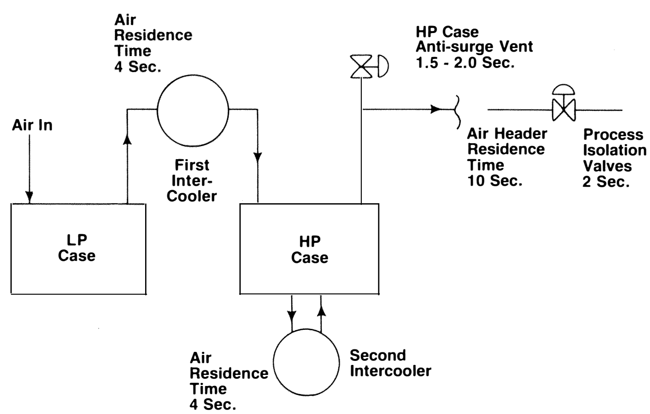

Figure 14. Air System Residence Time and Valve Stroking Speeds.

BOOSTER TUNING AND DEADBANDS

The first series of tests capitalized on the high gain function of the dual gain controller, and substantially increased system response. The high resolution data indicated that system dead-band and phase lags were also very significant parts of the problem.

The second phase of improvement concentrated on minimizing these deadbands. The first improvement was to the controller high limiter setting. The purpose of this is to prevent improper controller response due to integral or reset action. Some deadband is necessary to allow seating of the anti-surge valve to prevent leakage. However, step input tests showed that increasing the high limit voltage from 102 percent to 104 percent doubled the valve delay time from 0.15 sec to 0.30 sec.

Another deadband that was changed was for the air volume boosters on the anti-surge control valve (Figure 15).

These devices are to amplify the control signal, if it changes rapidly enough, otherwise the control signal is directly applied to the piston. The boosters also have a non-linear gain. This deadband is adjustable. If this adjustment is incorrectly set, the valve varies 15 percent to 20 percent with a fixed input control signal.

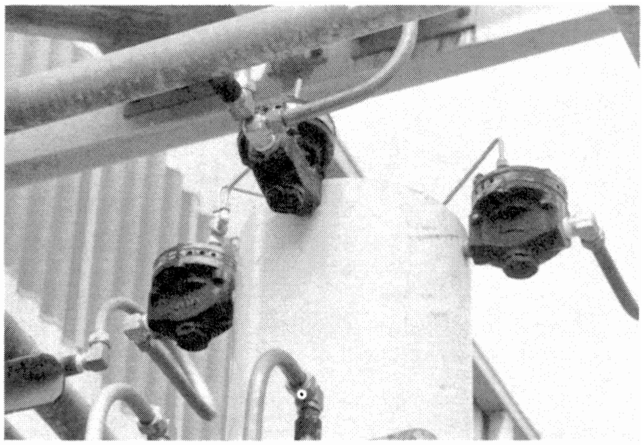

Figure 15. Air Volume Boosters on Actuator of the Anti-Surge Valve.

Clearly some deadband had to be provided. Since compressor flow signal noise was measured to be about two percent, three percent booster deadband was chosen. There was no direct way to set the deadband for the boosters. A square wave signal was therefore applied to the valve at three percent deadline amplitude. The boosters were then adjusted to start responding with this signal. The frequency response of the valve was markedly improved as was demonstrated for a swept sine wave input signal (Figures 16 and 17).

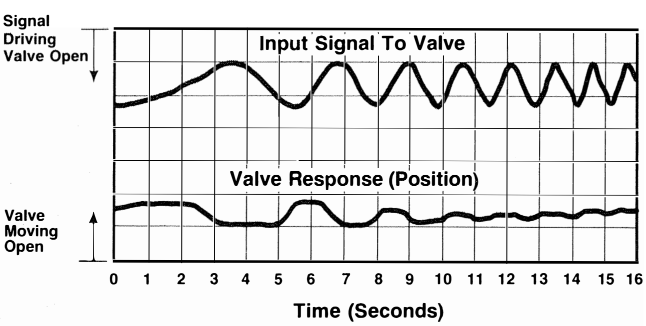

Figure 16. Anti-Surge Valve Response before Tuning the Boosters.

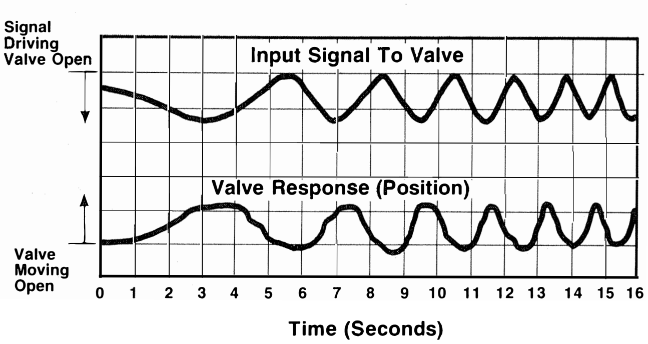

Figure 17. Anti-Surge Valve Response after Tuning the Boosters.

Due to these adjustments, total valve stroke time in response to a step input was reduced from 1.9 sec to 1.25 sec. The valve purchase specification required a response time of two sec or less.

PROCESS FEEDFORWARD

The final online test, in which all three of the reactors were shut down, showed that the anti-surge valve needed to react sooner (Figure 12). Feedforward information from the process was required. The first attempt at correcting this problem was opening the valve by 60 percent in the event that the three reactors shut down simultaneously. This method for quickening the anti-surge valve response worked and kept the compressor online during a plant upset soon after its installation, thus proving the value of feedforward information from the process. This impulse circuit was basically designed, however, for one size of plant upset. The impulse circuit also had the disadvantage of overshooting and could shut down the entire process on low header pressure.

The compressor ran for nearly a year before another surge occurred, in which all the reactors shut down at once, and the 60 percent impulse was not enough compensation. A more generalized impulse was needed, which could respond to any size air flow reduction.

SETPOINT IMPULSE

The one major remaining deadband in the HPC anti-surge control scheme was one that was deliberate (Figure 9). The spillback air control line is deliberately placed to the left of the anti-surge control line to force any excess air to be routed to the expander instead of venting. However, this control becomes a disadvantage during upsets. The anti-surge controller does nothing until flow drops to the anti-surge line, during which the margin from the surge line is lost. As the final phase in the program, it was proposed to impulse the setpoint [2] of the anti-surge controller (Figure 18). During the setpoint impulse, the anti-surge control line is temporarily moved

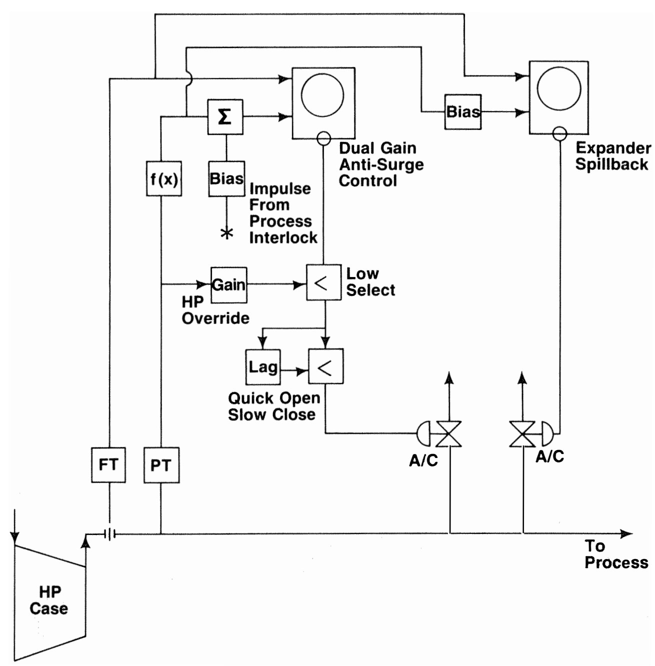

Figure 18. Final Control Scheme after Adding a Setpoint Impulse (Actuated by the Process).

slightly to the right of the spillback air control line. This provides the double benefit of increasing the margin from surge and forces the anti-surge valve into motion sooner.

During an online test, and numerous plant upsets since the modifications, the impulse has proven to have adequate response to prevent surge and thus keeps both the compressor and process online.

CONCLUSION

The effect that turbomachinery performance can have on the overall process is often important. This is a case where the effect of the process on the turbomachinery was very significant. Process shutdown was rapid and tape recording of the process data was valuable in understanding the system behavior. It was possible to simulate the behavior of the complete control loop by using the dynamic input signal from the tape recorder. In fact, tuning of the air volume boosters would have been difficult to do any other way. The simulation also made it possible to identify the deadband behaviors in the system.

The computer model showed good agreement for the milder compressor upsets. In order to account for the most severe upsets, it became necessary to include the effects of the intercooler volumes, since the compressor was operating in a transient state. The shape of the characteristic head curve at minimum flow forced the new compressor train to absorb all of the upset. The control circuits required the utilization of a high gain, low flow override to enable the control scheme to handle widely divergent needs. Impulsing the flow setpoint removed the last system deadband, making it possible to prevent the compressor from surging during the most severe upsets.

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