Advanced Multivariable Control of a Turboexpander Plant

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ABSTRACT

This paper describes an application of advanced multivariable control on a natural gas plant and compares its performance to the previous conventional feed-back control. This control algorithm utilizes simple models from existing plant data and/or plant tests to hold the process at the desired operating point in the presence of disturbances and changes in operating conditions. The control software is able to accomplish this due to effective handling of process variable interaction, constraint avoidance, and feed-forward of measured disturbances. The economic benefit of improved control lies in operating closer to the process constraints while avoiding significant violations. The South Texas facility where this controller was implemented experienced reduced variability in process conditions which increased liquids recovery because the plant was able to operate much closer to the customer specified impurity constraint. An additional benefit of this implementation of multivariable control is the ability to set performance criteria beyond simple setpoints, including process variable constraints, relative variable merit, and optimizing use of manipulated variables. The paper also details the control scheme applied to the complex turboexpander process and some of the safety features included to improve reliability.

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INTRODUCTION

The UPR Gulf Plains Plant located 13 miles northwest of Bishop, Texas has been processing gas from the nearby Stratton gas field for more than 50 years. The plant upgraded to a distributed control system (DCS) in 1991 and is in the process of expanding to handle significantly more gas. A large portion of this new gas supply is off-gas from a nearby refinery. The refinery gas has a major impact on plant operation due to its much higher liquids content than the native gas (18 GPM vs. 3 GPM). With its high liquid content, the refinery gas brings more frequent and larger disturbances in composition and flow rate. The variation in the new gas and the approach to equipment limits make the plant a prime candidate for advanced multivariable control.

Computer-based multivariable control has found industrial application since the 1970's, but only recently has it been applied to natural gas plants[1]. Figure 1 shows how multivariable control differs from single variable control. Single variable control ties one controlled variable (temperature, pressure, product quality) to one manipulated variable (valve position, setpoint, or engine run-stop switch). In cases where the number of controlled variables and manipulated variables are not equal, cascade or high/low select systems must be developed. Disturbance variables are not typically utilized in conventional single variable control. Multivariable control incorporates all available process measurements to calculate the best trajectory for the controlled variables.

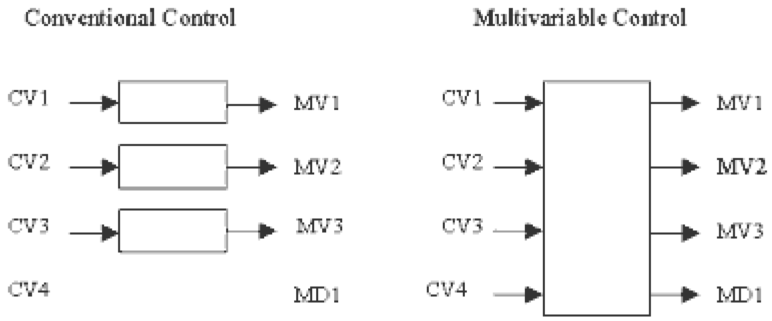

Figure 1: Comparison of Single Variable Control to Multivariable Control

PROCESS DESCRIPTION

The Gulf Plains Plant is a turbo-expander plant originally designed to handle approximately 120 MMSCFD of 3 GPM gas using one train. The plant currently processes 83 MMSCFD and is in the process of expanding its capacity to 135 MMSCFD. The gas is compressed, cryogenically separated, and fractionated to yield residue gas, ethane, propane, butane, and natural gasoline products.

One of the most important elements of the plant is the inlet cooling and demethanizer section shown in Figure 2. The main gas stream is cooled by low pressure residue gas and a propane chiller. A chiller bypass valve is available to help eliminate cold spins. The trim heater raises the temperature of the sidestream to heat the demethanized liquid product, as well as supply heat to the bottom and side reboiler. The turboexpander further cools the gas to about –165°F prior to demethanizing.

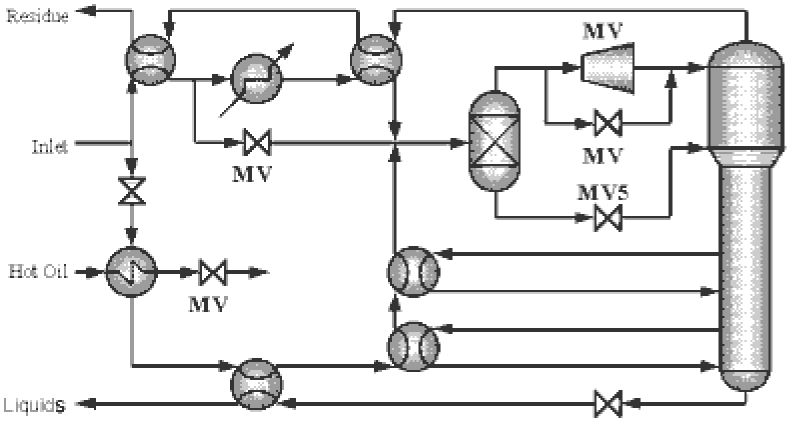

Figure 2: UPR Gulf Plains Plant Demethanizer

After the liquid product leaves the demethanizer, it is further fractionated by the deethanizer, depropanizer, and debutanizer. With the additional liquids production from the refinery gas, the deethanizer is a limiting unit of the fractionation train. As a result, a Y-Grade product will be produced in the interim until a new deethanizer can be constructed.

MULTIVARIABLE CONTROL

The goal of process control is two-fold: reduce process variability and keep the process at the desired operating point. A conventional feed-back system such as proportional-integral-derivative (PID) control, is an effective choice to meet these goals. However, in the tightly-integrated, constrained environment of the natural gas processing plant, even the most clever PID system can fail to meet the safety, environmental, and production requirements needed for maximum profit. The economic incentive for process control is that with reduced variability, the process can operate closer to constraints, which is where maximum throughput and/or efficiency is achieved[2].

Multivariable control techniques make calculations to optimize the response of the next move based on a large number of process measurements, a knowledge of the interdependence of each process variable, and a prediction of the output response. Multivariable control creates reduced process variability in several ways.

Process Interaction

Process conditions are highly dependent on many control elements because of the degree of heat cross-exchange, material recycle, and the short time constant of the gas stream. For example, the vane opening of a turboexpander affects not only the outlet conditions of the expander, but also those of the inlet separator and the inlet gas flow. Multivariable control takes into account the effect of each control element on the relevant controlled variables and compensates for the interaction accordingly.

Constraint Handling

Optimum performance is often achieved by operating ‘on the edge’, that is, at the limits of the product and process constraints. This type of operation risks violating limits if a disturbance enters the process and is not properly handled by the control system. Multivariable control is able to predict a future path for the constrained variables and determines the control move to explicitly avoid violating these limits. This allows operation closer to process optimum, with less risk of going over ‘the edge’.

Feed-forward of Disturbances

There are many instances where a disturbance can be identified before it has a negative impact on the final product. While feed-forward regulation of disturbances is possible in conventional control systems with significant effort, multivariable control seamlessly compensates for measured disturbances to reduce their influence on all controlled variables.

Control of Unmeasured / Infrequently Measured Variables

The final product quality measurement depends on a gas chromatograph reading that can be infrequent and delayed by several minutes. Conventional feed-back control action based on such a measurement must be strongly detuned to maintain the stability of the process which results in sluggish response to disturbances. Because the future path of all measured (and controlled) variables is forecasted, multivariable control is able to take appropriately aggressive action to maintain the infrequently measured or unmeasured variable at its setpoint.

Specification of Performance Requirements

The multivariable controller can be tuned so that process performance directly reflects the process specifications. For example, if one controlled variable has greater importance than all others, then a greater fraction of the control effort will be focused on that variable, allowing tighter control, while sacrificing some performance in the other less important variables. In many cases a controlled variable merely needs to be kept in a given range, rather than at a specific setpoint. If the constraint-handling part of the software determines that the trajectory of the system does not violate the specified limits, the controller can then concentrate its actions on the more vital objectives.

Process Review

Advanced control requires a detailed process review for proper implementation. A byproduct of this analysis is a greater understanding of the process and equipment, often resulting in process improvements.

CONTROL TECHNOLOGY

The core of the ControlMax^{TM} advanced multivariable control system developed by Bryan Research and Engineering is the minimization of an objective function that describes the desired performance of the process. The objective function includes terms for controlled and manipulated variable setpoint deviation, as well as manipulated variable move suppression. The controlled variable setpoint term allows setpoint tracking similar to the integral action of a PID loop. The manipulated variable setpoint term allows for optimal use of manipulated variables by directing the variable to a target value. The manipulated variable move suppression term minimizes excessive control action and leads to 'smoother' performance. A weighting factor is used to assign a relative emphasis on each term of the objective function.

In addition to the desired variable setpoints in the objective function, the controller must also respect process constraints. The multivariable controller must be aware of manipulated variable constraints to avoid exceeding operating limits of the equipment. These include physical valve limits and safety considerations. In addition, the predictive nature of the multivariable controller allows the process to not only minimize current constraint violations, but also to avoid future violations. Weighting factors place an importance on the constraints relative to each other and setpoint control.

The multivariable control package runs on a PC under the Windows NT operating system. The PC communicates with the plant DCS through an ethernet connection and has the ability to read and write information to the DCS. In the event of a communication or computer failure, a timeout system programmed into the DCS returns each process variable to its conventional control configuration. In addition, the multivariable controller is also compatible with the equipment safety systems or other plant overrides and in the event of an emergency the multivariable control system may be shut off by the operator at the PC or DCS.

APPLICATION

The ControlMax multivariable model-based control system has thus far been applied to the demethanizer, deethanizer, and C_1/C_2 product control at the Gulf Plains plant.

The first step of the implementation procedure was to simulate the process at steady-state. The commercial package PROSIM®[3] was used to give rough estimates of process gains[4]. In addition, time constants were approximated from design specifications and process knowledge. These initial studies serve to maximize the effectiveness of plant testing. The second step of the procedure was to determine the process performance requirements. This includes the relative importance of the many controlled and manipulated variables, constraint values, and an evaluation of the existing control strategy. Table 1 shows the variables used in the demethanizer controller.

Table 1. Demethanizer Controller Variables

Controlled Variables	Manipulated Variables	Disturbances
Inlet Separator Pressure	Sidestream Valve	Inlet Temperature
Demethanizer Pressure	Chiller Bypass Valve	Regeneration Gas Flow
Inlet Separator Temperature	Expander Vane Position	Inlet Compression HP
Bottoms Product Temperature	JT Valve	Residue Compression HP
Expander Speed	Separator Liquid Valve	Bottoms Product Valve
Separator Liquid Level	Trim Heater Valve	
Trim Heater Temperature		

The demethanizer and separator pressures were specified with an upper and lower constraint corresponding to equipment or operating limits. Both pressures also had moderately weighted setpoints to keep them at intermediate values during normal operation. The inlet separator temperature was specified with a lower constraint to avoid the cold spin condition. The bottoms product temperature was the highest weighted variable in the controller. This temperature, combined with the column pressure dictates the C_1/C_2 ratio of the product. This variable was specified with a heavily weighted setpoint to maintain product quality. The expander has a maximum allowable speed, which is explicitly avoided with an upper constraint. The exact value of separator level is not vital to the operation of the column, so it was specified with a weak setpoint, but also with upper and lower constraints to avoid spilling liquid into the expander or emptying the separator. The trim heater temperature has a strong influence on the operation of the deethanizer, so it was specified with a setpoint.

Due to the slower sampling time of the chromatograph, a second controller was used to predict and control the C_1/C_2 ratio. This information was then used to update the demethanizer setpoints.

All manipulated variables in the process were assigned an upper and lower limit based on their physical limitations. The manipulated variables also have maximum move sizes and move weights. The JT valve and chiller bypass valve had setpoints specified to them. In normal operation, the expander will be able to handle all vapor flows into the demethanizer, and for the sake of efficiency it should be used in preference to the JT valve. To achieve this, the JT valve was assigned a setpoint of 0.0 to tend to keep it closed. It is allowed to open and operate in abnormal situations if the expander cannot meet all performance requirements. The chiller bypass valve also has a setpoint of zero to minimize its use. The expander was assigned a weak setpoint corresponding to its optimal design point, in order to push the expander to this point as all other specifications are met.

There are many potential disturbances to a gas plant, but not all are measured. One of the obvious measured disturbances is the inlet gas temperature at the outlet of the molecular sieve dehydrator beds. This value is generally very steady, however, during a bed change the temperature of the gas leaving the regenerated bed spikes up, sometimes by 30°F, before settling back to normal. This disturbance has a severe effect on column operation and product quality. A second disturbance related to the dehydrator bed change is the regeneration gas flow rate. This gas is taken from the residue system and can disturb column pressure when it first begins to flow. There are other known disturbances associated with these bed changes that cannot be explicitly utilized because they are not connected to the DCS.

One of the largest disturbances a gas plant undergoes on a regular basis is the loss of inlet or residue compression. To account for compressor engines going on or off line, the engine run-stop signals are input to the controller. The total online compression horsepower is then calculated by the controller using the following expression:

$$HP = \sum_{i=1}^{N} x_i \, HP_i$$

N	Number of compressor engines
x_i	1 if engine *i* is running, 0 if not
HP_i	Nominal horsepower of engine *i*

The last disturbance is the valve position of the bottoms product liquid level controller. Because this stream is cross exchanged with the sidestream, it affects the temperature control of the process.

Having specified the controller variables and performance requirements of the process, the next step was to test the dynamic response of the plant to changes in the manipulated and disturbance variables. Testing was primarily performed with the existing control system set on manual using step changes, however some closed-loop data was used for model identification. Multiple tests are run for each manipulated variable to confirm model parameters and check for nonlinearity or improperly acting variables. The plant testing also served to confirm variable interaction. As an example, the sidestream valve was found to impact the bottoms temperature, separator temperature, trim heater temperature, separator pressure, expander speed, and to a smaller extent, the separator level.

Once the process models were constructed, the controller was tested and initially tuned with an off-line simulator. This simulator is part of the control package and lets the user explore performance relative to a nominal or mismatched plant model. The controller was then put on-line and further tuned to achieve the desired performance.

CONTROLLER PERFORMANCE

The controller was able to smooth the operation of the demethanizer noticeably. The C_1/C_2 ratio is the primary product specification and as such has the largest control emphasis. Figure 3 shows the response of the C_1/C_2 control during a dehydrator bed change for the DCS control and the multivariable controller. The two responses were obviously taken at different times, but the prior plant behavior and the nature of the disturbance should be comparable. The multivariable controller resists the initial temperature spike (shown by the drop in C_1/C_2 ratio for the DCS) and returns the C_1/C_2 back to setpoint much faster than the DCS. The dropout in the C1/C2 ratio at 80 minutes for the multivariable controller was caused by an unmeasured compressor engine being brought into service. The standard deviation of the C_1/C_2 ratio dropped from 0.35 under the DCS control to 0.20 with the multivariable controller.

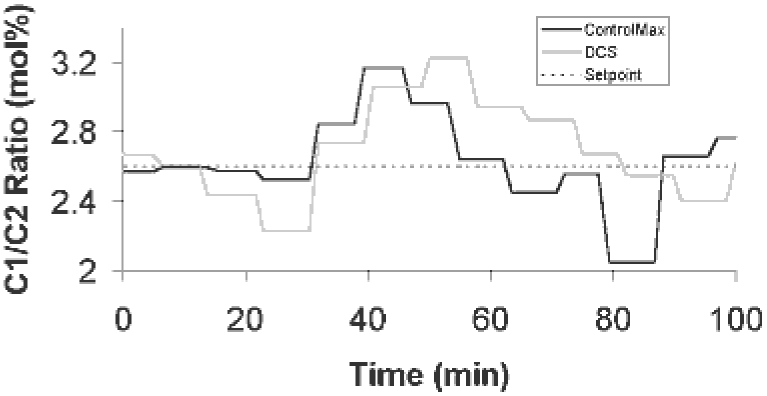

Figure 3: Comparison of DCS to ControlMax Performance

The process frequently operated at the lower constraint of the inlet separator pressure. The controller minimized violations of this constraint while still maintaining product quality. The controller allowed the inlet separator liquid level to float in order to minimize feed disturbances to the column. These feed variations were found to be a consistent problem with the column operation, especially the pressure.

By reducing process and product variability, the multivariable controller allows the demethanizer to operate more efficiently. Smooth operation can increase C2 recovery and reduce energy cost of compression, chilling, and hot oil. In addition to improving the behavior of the demethanizer, good control of the front end of the plant reduces disturbances and increases efficiency of the deethanizer and all downstream operations.

OTHER RESULTS

The effective operation of any control system is dependent on the reliable operation of the underlying measurements and actuators. This is especially true for predictive model-based control. With conventional single-variable control, if an actuator or measurement fails to respond properly, only that controller is directly impacted. A multivariable controller takes action on all manipulated variables based on the belief that all controlled variables will respond to those moves as expected. A bad control element can directly affect the entire controller. This need for a properly operating process can be seen as an advantage for multivariable control, as it forces a process review for bad acting elements, usually during plant simulation or testing.

Gas chromatographs can be a frequent source of measurement difficulty. During the process review of the demethanizer, the C_1/C_2 measurement was found to have a deadtime of over an hour, despite sampling every 20 minutes. This measurement lag was causing severe problems with the DCS controller. For example, the process took five hours to settle back to the setpoint after a dehydrator bed change. On further study of the measurement system, the valve on the sample line was found to be almost entirely shut, in order to minimize the pressure drop of the liquid sample (Figure 4). Simulation showed that the liquid sample could undergo a much larger pressure drop without fear of flashing. Opening the valve on the sample bypass line allowed for normal performance of the chromatograph measurement.

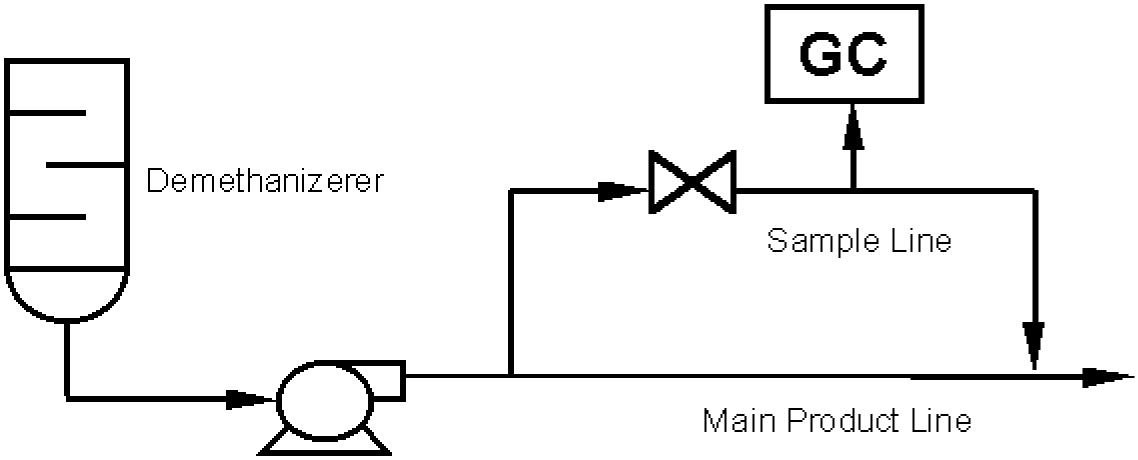

Figure 4: Schematic Diagram of the GC System

One common problem with control valves can be the phenomenon of hysteresis or deadband operation, both shown in Figure 5. Hysteresis is characterized by a lack of valve response when the output signal to the valve changes direction. Once the signal crosses the ‘no mans land’ the valve responds normally until the signal again changes direction. This is often caused by slack in the actuating mechanism. Dead band response can also be caused by a fixed region, as opposed to hysteresis where the region moves with the signal. A common cause for fixed dead band behavior is a split range valve where the upper range of one valve is not matched up with the lower range of the other.

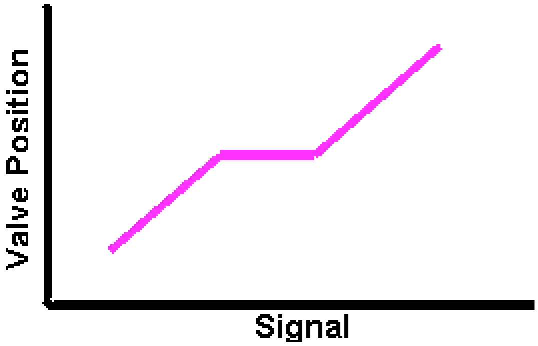

Figure 5a: Valve Deadband

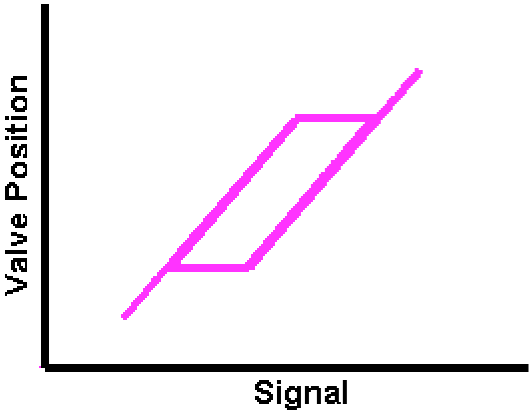

Figure 5b: Valve Hysteresis

Figure 6 shows an example of hysteresis in the response of the trim heater valve. In several instances, the signal moves with no response by the outlet temperature. In this case, the dead band was approximately 2%, which was significant because of the sensitivity of the controlled variable response. The ControlMax multivariable control system explicitly accounts for this type of behavior and effectively manipulates the valve.

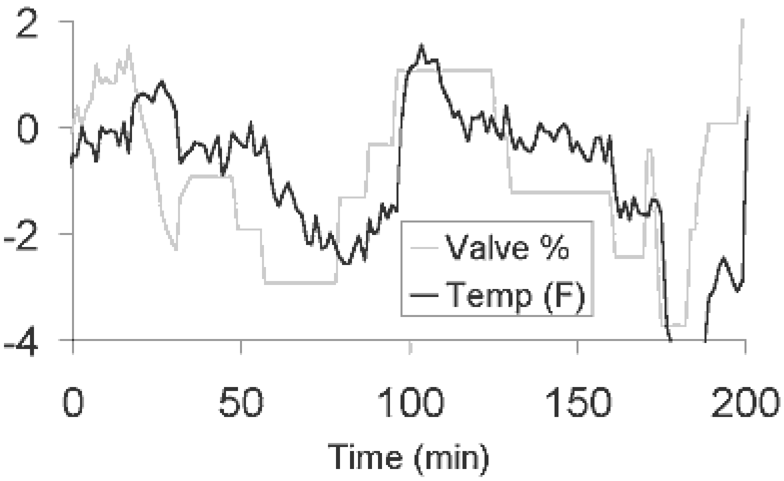

Figure 6: Hysteresis in the Trim Heater Valve

In some cases, improperly functioning equipment can inhibit the predictability of the process. For example, in the deethanizer controller, the feed tank showed a higher pressure than calculated by simulation. Due to this pressure error, estimated gains differed noticeably from the identified models. Upon examination of the process, the ethane product recycle valve was found to be leaking high pressure ethane into the feed tank. After closing the block valve, the process responded more like the modeled behavior. In addition to improving process control, eliminating the ethane recycle also reduced the load on the chilling system, product treatment and product compression.

SUMMARY

The advanced multivariable control system ControlMax was applied to a cryogenic demethanizer system to improve performance in the presence of a new gas stream. The control technology selects multivariable moves to simultaneously meet the plant performance requirements, while still obeying process and equipment constraints. The control system was able to maintain tighter control of setpoints, particularly the demethanizer product quality. In the process of applying the advanced controller, several operating difficulties were identified and either corrected in the field or mitigated in the controller. In addition to the demethanizer, the control package has been applied to other plant units as a part of an overall process control and optimization project, and is expected to yield significant economic improvements.

ACKNOWLEDGEMENTS

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