Implementing Mid Ranging in a DCS Environment

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Abstract: Mid ranging is an algorithm for controlling one control variable, such as flow or pressure, with two manipulated variables. Although mid ranging is a very well established technique there are a number of practical issues which must be addressed when implementing mid ranging in the DCS. These issues include handicapped operation, bump less transfer and proper handling of saturation conditions. In this article, an algorithm for mid ranging is presented which exploits the inbuilt functionality of the control blocks in a modern DCS. A specific feature of the algorithm is the ability to maintain control even when one of the manipulated variables is out of service. Finally the article also demonstrates how the algorithm is extended to handle three manipulated variables.

Keywords: Mid ranging, Distributed Control System, Integral Control, External Reset Feedback.

1. INTRODUCTION

Mid ranging is an algorithm in which two control handles are manipulated to control one control variable. The most common process application for mid ranging is when flow or pressure is controlled using two valves of different size situated in parallel.

Typically, control valves with high flow capacity have poor control characteristics at the extremities of the control range. To circumvent this problem, a small valve with favourable flow characteristics at low flows is installed in parallel with the large valve. The purpose of mid ranging control is to coordinate the actions of the small and large valves to achieve fine control of flow over a wide range.

One of the most common examples of the parallel valve configuration is pressure control of fuel gas in fired furnaces. When the furnace is on standby, highly accurate pressure control of fuel gas is required to achieve the correct firing conditions in the burners. This can only be achieved using a small control valve. At normal firing loads the larger valve is required to accommodate the much higher fuel demand.

Several solutions to the mid ranging control problem have been reported in the academic literature including valve position control (VPC), hybrid control and model predictive control (MPC). VPC is the most popular strategy on the basis of simplicity and ease of implementation. However the VPC is recognised to be difficult to tune and can yield suboptimal control in the presence of saturation. Tuning methods for VPC based on internal model control (IMC) principles have been proposed in Allison and Isaksson (1998) and Gayadeen and Heath (2009) and alternative anti windup strategies are described in Gayadeen and Heath (2009) and Haugwitz (2007).

The MPC solution for mid ranging control is shown in Allison and Ogawa (2003) to give superior performance over the other methods in the presence of saturation, or when the process dynamics are complex. MPC is also ideally suited to handling the handicapped mode of operation in which one of the control valves is out of service. However, it is noted that due to the cost and complexity of installing MPC, it is unlikely that this technology can be justified for mid ranging control unless it forms part of a wider control strategy.

In the last section of this report, an algorithm for mid ranging based on the sliding split range concept is described. This algorithm is similar to the hybrid algorithm described in Allison and Isaksson (1998), with the distinguishing feature that it exploits the built in functionality of the DCS to deal with the issues of handicapped operation, bump-less transfer and saturation. The algorithm thereby avoids the complexity of transfer function based solutions from the literature which can become complex and difficult to maintain when logic for mode switching, initialisation and windup propagation is imposed.

2. CONTROL USING TWO PARALLEL VALVES

The simplest control scheme for the two parallel valve configuration is two separate controllers as illustrated in Figure 1. In this example from a fired furnace at a Borealis cracker plant, pressure controller PC1 controls the flow through the small line only, and PC2 controls the large flow.

![Diagram of parallel valve control system](image-url)
Figure 1 Pressure Control using Separate PCs

Control of parallel valves using two separate controllers generally works well when the operating window can be divided into two distinct ranges. In this case only one of the flow controllers is needed at any one time, and the other can simply be placed in MAN mode and fully closed.

The major pitfall of the two controller scheme is observed in the transition region. In this region a flow is required which is near the maximum capacity of the small valve. To achieve the desired flow the operator must juggle the setpoints and modes of both the PCs.

Automatic transitioning between the small and large valve ranges can be achieved using a conventional split range strategy as illustrated in Figure 2. The split range strategy works by dividing the output from the main controller into two valve signals as defined by a split range profile as shown in Figure 3.

The breakpoint in the split range profile is placed in order to achieve a linear flow characteristic over the whole OP range. In this example, the capacity of the large valve is 4 times greater than the small valve, which is why the breakpoint is placed at 20%.

Figure 2 Split Range Flow Control

Figure 3 Split Range Profile

In practice, the split range scheme exhibits poor control in the transition region because the large valve often has poor flow characteristics when it is barely open. A sporadic and/or highly non-linear flow response of the large valve in this regime makes fine control of flow impossible.

The handicapped mode of operation, in which one of the valves is in MAN mode, and the 3 valve configuration can also be accommodated in both schemes.

3. MID RANGING CONTROL

The purpose of mid ranging is to provide achieve good flow control over the range of capacity for the two parallel valves. The underlying principle is that fine continuous control is done by quick movements of the small valve while the bulk flow is accommodated by slow positioning of the large valve. The 2 valves are orchestrated to the tasks they do best. It can also be argued that the mid ranging algorithm reduces overall maintenance costs by minimising the accumulated travel of the large valve.

The steady state behaviour of the mid ranging algorithm is illustrated in Figure 4. The key feature of the algorithm is that only the small valve is used at the extremities of the flow range. As the small valve is in the middle of its control range when the large valve begins to open, it is capable of compensating for the sporadic and/or non-linear flow characteristic of the large valve. In the middle of the flow range, the small valve converges to the middle of its control range, and the flow demand is met by the large valve.

The dynamics of the mid ranging scheme are illustrated in Figure 5. In this simulation, a load change from 20% to 25% (blue trend) causes a quick corrective move of the small valve (yellow trend) from 50% to 75%, after which it retreats back to 50%. In the meantime the big valve (purple trend) moves slowly from 12.5% to the new steady state at 18.75% as required.

Figure 4 Steady State Characteristic for Mid Ranging

Figure 5 Dynamics of Mid Ranging
3.1 Valve Position Control

Mid ranging control is most often implemented using the Valve Position Control scheme as illustrated in Figure 6. In VPC, normal flow control is done using the FC connected to the small valve. The valve position control part of the scheme is performed by the second PID controller (ZC) connected to the large valve. The process value of the ZC is fetched from the output of the FC and corresponds to the position of the small valve. The VPC thereby employs the large valve to achieve a desired position of the small valve (typically 50%) via the feedback action of the FC. The VPC scheme is capable of excellent flow control over a wide flow range on the basis that flow control is always done using the small valve. The scheme is also simple to configure in the DCS, and easy for operators to use which justifies its widespread use in industry.

As discussed in the literature, there are some challenges associated with tuning of the VPC scheme. As a general rule, the ZC is tuned more slowly than the FC so that movements of the large valve are slower than the small valve. When tuning the FC it should be recognised that the nesting of the loops results in a change of the FC open loop dynamics from self-regulating to lead plus integration.

The major disadvantage of the VPC scheme is that it cannot operate in handicapped mode. If the small valve is out of service, both the FC and the ZC must be placed out of service. If this is not done, the integrating action of the ZC will drive the large valve into saturation. In practice, an interlock is required to force the ZC to MAN when the small valve is in MAN. A second disadvantage of the VPC scheme is that there is no obvious extension to 3 valves.

4. MID RANGING CONTROL WITH SLIDING SPLIT RANGE

The control structure for the mid ranging based on the sliding split range is depicted in Figure 7. As shown, the scheme comprises a valve position controller (ZC) plus the sliding split range function. The scheme is in fact a combination of a split range scheme (Figure 2) and the VPC scheme (Figure 6) and as such inherits the advantages of both schemes at the cost of a marginal increase in complexity.

The block diagram for the whole mid ranging control scheme is shown in Figure 8. The sliding split range part of algorithm, which includes everything beside the FC and ZC controllers, is a set of gain and addition blocks. In addition, limits are placed on the absolute value and rate of change of the valve output signals.

4.1 DCS Implementation

The DCS implementation of the sliding split range is shown in Figure 9. Only three DCS blocks are required, including one signal splitter block and two scale/bias blocks. The order of execution of the blocks as shown in the upper right hand corner is critical for the logic to work as designed.
In practice, the units for \( C_v_1 \) and \( C_v_2 \) are irrelevant, as long as the ratio of these two numbers corresponds to the ratio of the flow capacities of the two valves. In the absence of valve sizing sheets, the trim sizes can be used as a first estimate for \( C_v_1 \) and \( C_v_2 \). A better approximation is the linear process gains obtained from step testing of the valves.

### 4.3 VPC Controller

As previously, a VPC controller (ZC) is used to manipulate the large valve in order to achieve the desired position of the small valve. When used in conjunction with sliding split range algorithm, the output of the VPC acts indirectly on the large valve via the bias term of the first scale/bias block.

The VPC function is implemented via an I-only controller. Proportional and derivative action is not required in this case as the input/output dynamics of this system are instantaneous. There is only one tuning constant for the I-only controller, the integral time \( T_i \).

The transfer function for the I-only controller is given by:

\[
    u_2 = \frac{1}{T_i s} \cdot OP_1(s)
\]

From which it can be shown that the open loop dynamics between the load signal \( u_1 \) and the small valve position is given by:

\[
    \frac{OP_1(s)}{u_1(s)} = \frac{C_v_1 + C_v_2}{C_v_2} \cdot \frac{T_i s}{C_v_1/C_v_2 \cdot T_i s + 1}
\]

This is a zero gain model for which the time constant is related to the ratio of the valve sizes and the integral time. Similarly the open loop dynamics between \( u_1 \) and \( OP_2 \) are given by:

\[
    \frac{OP_2(s)}{u_1(s)} = \frac{C_v_1 + C_v_2}{C_v_2} \cdot \frac{1}{C_v_1/C_v_2 \cdot T_i s + 1}
\]

This is a first order model with steady state gain \((C_v_1+C_v_2)/C_v_2\) and the same time constant for the small valve dynamics.

The above relationships make tuning for the ZC easy on the basis that the desired lag for the large valve is tuned via the integral time. A rule of thumb for tuning the ZC is to set the integral time such that the time constant of the valve response equals the slew rate of the large valve. The slew rate is often reported on the valve test sheet. If step test data is available, the lag time constant plus the dead time of the flow dynamics can be used.

The ZC is equipped with external reset feedback because the output from this controller is connected to the bias input of the scale/bias block and not sent directly to the valve itself. At each execution of the ZC, the external reset feedback input is obtained from the final calculated output signal sent to the

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**Figure 9 Sliding Split Range Logic**

The DCS logic works as follows. First, the signal splitter block divides the output \( u_1 \) (range 0 – 100%) from the flow controller into two equal signals \( w_1 \) and \( w_2 \) according to:

\[
    w_1 = w_2 = (C_v_1 + C_v_2) \times u_1 / 100
\]

Where \( C_v_1 \) and \( C_v_2 \) are the valve capacity \( C_v \) values for the small and large valves respectively. The outputs \( w_1 \), \( w_2 \) from the splitter are in the range 0 to \((C_v_1+C_v_2)\). These signals represent the flow demand in valve capacity units.

Next, the first of the two scale/bias block executes the scale and bias calculation according to:

\[
    OP_1 = (w_1 - C_v_2 \times u_2 / 100) \times 100 / C_v_1
\]

Where \( u_2 \) is the output from the ZC (range 0 – 100%).

The output sent to the small valve (range 0 – 100%) is obtained by subtracting the desired position of the large valve from the total demand (in valve capacity units), and rescaling to 100%.

Finally the second scale/bias block executes according to:

\[
    OP_2 = (w_2 - C_v_1 \times OP_1 / 100) \times 100 / C_v_2
\]

The output sent to the large valve (range 0 – 100%) is obtained by subtracting the current position of the small valve from the total demand (in valve capacity units), and rescaling to 100%.

### 4.2 Valve Capacity Sizes

As shown, the scaling and bias calculations used within the sliding split range are based on the parameter constants \( C_v_1 \) and \( C_v_2 \). By definition, \( C_v_1 \) and \( C_v_2 \) are the valve capacity sizes for the small and the large valves respectively. The values can be read from the valve specification sheets and are typically given in units of m\(^3\)/(h.kPa\(^{1/2}\)).
large valve. External reset feedback means that the output is incremented from the actual valve position and not the valve position calculated by the controller at the previous execution.

Integral only control with external reset feedback is a standard option for PID control in most modern DCS systems.

Minimum, maximum or rate of change limitations can be placed on the valve outputs if mechanical limitations are present. The external reset feedback function applied to the ZC captures all such limitations in the overall anti windup strategy.

As a final note, it is assumed that all control blocks used in the mid ranging algorithm fully support initialisation via back calculation. Failure to implement the standard DCS mechanisms for initialisation in the cascade path will result in bumps and potential process disturbances when the valves are first switched from MAN to CAS mode.

4.4 Saturated Operation

As illustrated in Figure 4 control is performed exclusively by the small valve when the large valve is saturated. When the small valve saturates, as can happen following a large disturbance or set point change, the second scale/bias block ensures that the deficit in control action is supplied by the large valve. This condition continues until such time as the action of the large valve compensates for the load change and the small valve is able to retreat to its mid-range position.

There are two key elements to establishing the desired functionality at saturation. The first is that the bias input to the second scale/bias block corresponds to the actual position of the small valve. Any absolute or rate of change limitation imposed by the first scale/bias block is observed on this bias signal. The second key for handling windup is the use of external reset feedback for the ZC, which means that any limitations posed by the second scale/bias block are considered at the successive execution of the controller.

For example, consider what happens when the output of the flow controller reaches 90%. At this point the large valve is fully open, the output from the I-only controller is saturated at 100%, and the standard DCS mechanism for anti reset windup is applied to the ZC. Additional demand increase is accommodated by the small valve only until the output from the flow controller reaches 100% and the small valve becomes saturated. Now that both valves are 100% open, anti reset windup is applied to the flow controller.

4.5 Handicapped Operation

Control in handicapped mode is performed by the path between the flow controller and the active valve. Consider what happens when the large valve is in MAN and its position is under operator control. In this condition, the second scale/bias block and the I-only controller are forced to initialise to the actual position of the large valve. The first scale/bias block works as normal and manipulates the small valve in response to the total demand signal. The small valve will also compensate for any manual change in the position of the large valve. In this condition flow control will be maintained as long as the small valve does not saturate.

When the small valve is in MAN, flow control will be performed entirely by the large valve via the second scale/bias block. In this condition the first scale/bias block and the ZC are forced to initialise. Flow control is still possible, but of course will not be as precise as when the small valve is available.

For the case when both valves have first order flow dynamics with equal time constants it can be shown that the open loop transfer function between u1 and the total flow is given by:

$$ F(s) = \frac{CV_1 + CV_2}{100} \frac{1}{T_c s + 1} $$

Where $T_c$ is the time constant of both valves. This shows that the open loop dynamics generated by the mid range structure are the same, regardless if one or both valves are in service. Thanks to this property, no gain scheduling of the FC is required to handle the handicapped mode of operation.

In practice, the time constants of the valves are not identical and the open loop dynamics of the handicapped mode of operation will be different. Typically, this will be dealt with by appropriate tuning of the FC. However, if the deterioration in closed loop performance is unacceptable an enhancement to the control structure is required. The modification is in the form of a lead/lag element in the path to the small valve, the purpose of which is to slow down the dynamics of the small valve to match the large valve. The transfer function of the lead/lag element is:

$$ \frac{OP_{mod}(s)}{OP_1(s)} = \frac{T_{C_1} s + 1}{T_{C_2} s + 1} $$

Where $T_{C_1}$ and $T_{C_2}$ are the time constants of the small and large valves and $OP_{mod}$ is the (modified) output sent to the small valve.

In the DCS, the lead/lag element is constructed from a PI controller in feedback with itself. The PI controller acts as a positioner which manipulates the position of the small valve to achieve the desired OP value calculated by the mid ranging logic. The desired lead/lag dynamics are achieved by setting the gain of the PI controller to $T_{C_1}/(T_{C_2} - T_{C_1})$ and the integral time to $T_{C_1}$. The mid ranging scheme including the compensator is shown in Figure 10.
5. IMPLEMENTATION

The mid ranging algorithm based on the sliding split range was implemented at one of the Borealis polyolefins plants in Europe. Implementation was done first on a condenser temperature control application. The condenser is equipped with two control valves on the cooling water line. Previous attempts to establish temperature control using one or both of these valves were unsuccessful. The problem was solved elegantly using the mid ranging algorithm.

On the same unit, there are 6 feed flow arrangements consisting of 2 or 3 valves in parallel. This design facilitates the manufacture of different product grades according to recipes with widely different feed flow demands. In addition, feed flows are manipulated variables in an APC strategy.

In the original design individual flow controllers were used for the 2 or 3 valves which meant that transitioning between the flow ranges required manual action from the operator. In particular, APC control needed to be paused while the MV was changed, which was highly disruptive to production. The implementation of mid ranging for feed flow control circumvented this costly issue and improved the precision of feed flow control.

Figure 11 shows the results from one of the mid ranging controllers during 24 hours of operation with 5 min average values. As shown, excellent tracking of the measured total flow (red trend) to the setpoint from APC (blue dashed trend) is achieved. At first, only the small valve (green trend) is used. When the position of the small valve reaches 50% the mid ranging controller starts opening the larger valve (black trend). Around time 03:50 a large grade transition is started and the total feed flow is quickly increased from 3 to 73. The larger valve responds by opening quickly to keep the smaller valve around the desired position.

REFERENCES


