ADVANCED ANTI-SURGE CONTROL ALGORITHM FOR TURBINE DRIVEN CENTRIFUGAL COMPRESSORS

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***ABSTRACT*:** *Centrifugal compressors are widely used for natural gas transportation by increasing the pressure of the gas. Surge is an inherent phenomenon in a centrifugal compressor, defined as reversal of fluid flow which can possibly damage the machine. Anti-surge control is an important control for safety of the compressor and it can keep the compressor always running in the safe area right to the surge line. In this paper, simulation results of the surge phenomenon occurring in a centrifugal compressor in various conditions such as high header pressure, low suction pressure, start-up and emergency shutdown of the unit are presented and their control strategies are discussed. Dynamic simulation of the centrifugal compressor is carried out in HYSYS. Conventional PID and Advanced (PI plus Recycle Trip) controllers are implemented to check their performance. Advanced controller prove to be superior to simple PID controller in protecting the compressor in severe surge case. Start-up and shut down surge was prevented by fully opening the anti-surge control valve.*

Key Words: Surge Limit Line, Surge Control Line, Anti-Surge Controller, Deviation, Advanced PI plus RTL Response, Surge Parameter, Emergency Shutdown

INTRODUCTION

High pressure is required for the gas to be transported to commercial and industrial areas from remote well head places through pipelines. Compressors are used for this application to raise the pressure of the gas. A complete compression process consists of turbo-compressor unit, scrubbers, piping, control valves and coolers. [1] The incoming gas is first filtered to remove the foreign and dust particles, then it is passed to scrubbers where liquid droplets are removed to protect compressor from liquid entry damage. The compressed gas is then passed through coolers to allow the high temperature to decrease.

Surge

Surge is an inherent phenomenon in centrifugal compressors which can possibly damage the machine. It is defined as reversal of fluid flow. At this point, compressor peak head capability is reached and this is the point of minimum flow. Below it, the severe oscillations in flow and discharge pressure are created producing huge noise, large vibrations and consequently costly damage to the machine making the entire system unstable. At surge point, flow separation occurs inside the impellers making it unsteady and changes its direction. In order to avoid the problems associated with surge, an anti-surge control system is used to maintain a safe operating volumetric flow through the compressor. [2]

As shown in Fig. 1, the lower limit of the flow is termed as surge limit and the higher limit of flow is termed as choke limit (also stonewall limit). Above choke limit, the fluid flow reaches the speed of sound at a given speed and no further increase in flow becomes possible. The stable flow of the compressor is between these two limits. [3]

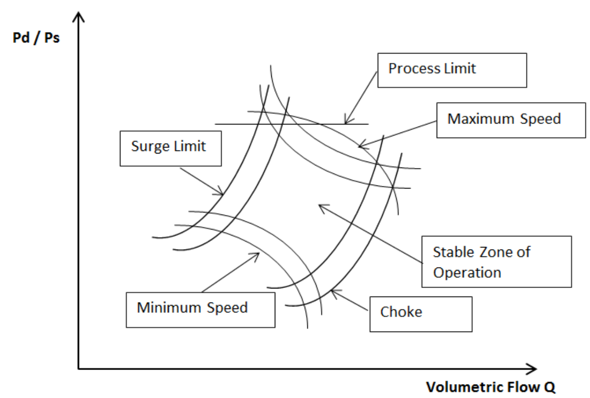

Figure 1. Compressor Characteristic Curve [3]

Surge is a cyclic phenomenon i.e., surge repeats unless a control action is taken to bring compressor out of surge. A complete surge cycle is shown in Fig. 2 in which the flow reversal and recovery is shown. It is a high speed phenomenon i.e., flow reversals can occur in less than 150 milliseconds. The intensity of surge varies from application to application and is proportional to the density of the fluid. Higher pressure and higher molecular weight applications can result in greater mechanical damage. [1-3]

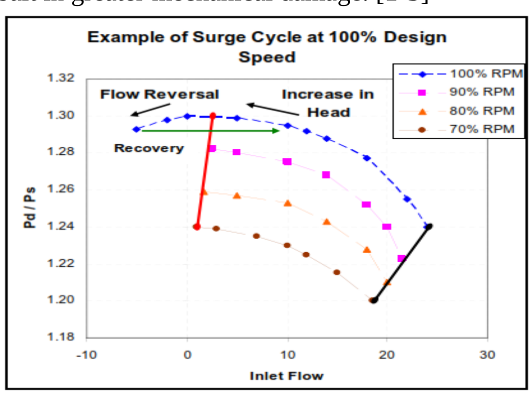

Figure 2. Surge Cycle [3]

The time domain profile of the surge is shown in Fig. 3 which shows that during surge condition flow reverses periodically and discharge pressure fluctuates.

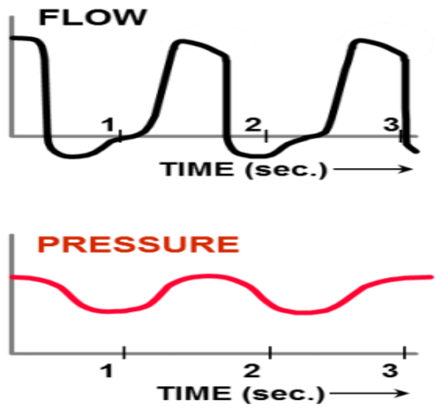

Figure 3. Time Domain Profile of Surge [5]

Causes of Surge

In the operation process of the compressor, surge mostly occurs during abnormal operating conditions such as pressure building in main header [P(header) > P(Discharge)], cut off / lower demand of flow, low suction pressure, start-up of unit and emergency shutdown of unit. The other possible causes of surge can be inlet valve failure that result in low flow, blockage of inlet filter, high pressure that is caused by the failure of outlet valve, failure or blockage of anti-surge control valve and human failure. [1-3]

Surge Prevention Techniques

The occurrence of surge can be prevented effectively by maintaining a certain minimum flow above a specified margin from the surge limit to keep the compressor running in stable zone of operation. This minimum flow is generally set at 1.1 times of the surge line flow in the same pressure ratio. This can be achieved by opening a blow-off valve at discharge line of compressor or by operating a recycle valve in the discharge process system. Blow off causes waste of expensive process fluid, therefore, recycling is preferred and mostly carried out through electronic 4-20mA operated control valve which is termed as anti-surge control valve. [1-3]

Anti-Surge Control System

Anti-surge control system is designed to determine the surge condition in compressor and to operate the anti-surge control valve in efficient and speedy manner to protect centrifugal compressor from surge. Fig. 4 represents a complete anti-surge control system as implemented in local gas compressor station.

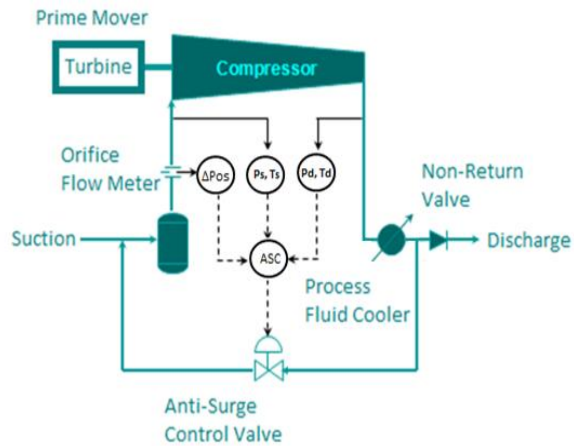

Figure 4. Anti-Surge Control System [3]

The components required in a complete surge control system are as follows:

Surge Detection and Control Algorithm: The main algorithm governing the protection of the compressor by taking input from suction and discharge transmitters, calculating surge parameter and deviation and generating output to anti-surge control valve for flow recycle.

Surge Limit Model: The surge limit model represents the surge pints at various speeds of the compressor. These are usually provided by vendor in datasheets and are also determined at site during commissioning of anti-surge controllers.

Actuation System: The anti-surge control valve or recycle valve receives input in terms of 4-20mA from anti-surge controller and protects the compressor. The selection of the right type of valve and its size is very important for effective surge control system.

System Instrumentation: The instrumentation includes suction pressure transmitter, suction temperature transmitter, suction flow orifice meter, discharge pressure transmitter and discharge temperature transmitter. Theses transmitters provide electronic 4-20mA signals to anti-surge controller according to their measuring scales. The selection of proper type of instrument is also very important for effective anti-surge control system.

Piping System: The compressor system piping determines the response time requirement for the recycle valve. Piping volume also influence the process control operation (precision of control and speed of response). [3]

Advanced Anti-Surge Control Algorithm

Avoidance control is the most commonly used surge control strategy for centrifugal compressors. In this control strategy, a control line termed as Surge Control Line (SCL) is defined at some distance from surge line called the surge margin and the operating point is restricted to the right of this control line. The distance between surge line and surge control line should not be too close, normally 10%-20%, because actuator's response time is not fast enough and fluctuations in operating point can drive the compressor into surge easily when operating conditions change. However, the compressor efficiency is maximum near the surge limit line. Hence in order to increase the compression efficiency, compressor's operating point should be close to surge line as far as possible. [1, 2]

In more advanced control system, a backup line closer to the surge line can also be defined which when crossed generates more aggressive action from the controller. Additionally a safety line can be added at surging conditions that if it is crossed it will further increase the surge margin in order to avoid surges in the future. These lines are shown in Fig. 5 below. [3]

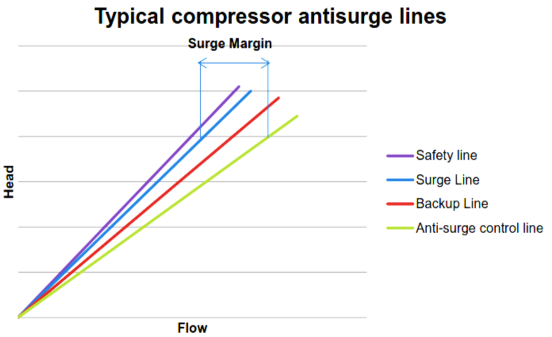

Figure 5. Safety and Control Lines in Control Algorithm [3]

The surge point is dependent on multiple parameters such as the molecular weight and flow into the compressor. In order to describe the surge line it is beneficial to use a coordinate system that is invariant or nearly invariant of the inlet conditions. There are several possible coordinate systems that satisfy the required conditions and one of the mostly used is reduced polytrophic head versus the reduced suction flow rate squared. [4]

Compressor pressure ratio 'Rc' is defined as [5]:

$$R_C = \frac{P_d}{P_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

Where 'Pd' is discharge pressure of compressor and 'Ps' is suction pressure of compressor. Parameter polytrophic head exponent 'σ' is defined as[5]:

$$\sigma = \frac{\log\left(T_d / T_s\right)}{\log\left(P_d / P_s\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots 2$$

Where 'Td' is discharge temperature of compressor and 'Ts' is suction temperature of compressor. Reduced pressure head 'hr' which incorporates both temperature and pressure effects is defined as [5]:

$$h_r = \frac{\left(R_c^{\sigma} - 1\right)}{\sigma} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

Mostly, orifice type flow meter is used in industry for flow measurement applications due to its accuracy and simplicity. In this algorithm, reduced flow 'qr2' is used which is the ratio of differential pressure across orifice plate 'ΔPos ' as given by flow transmitter and the suction pressure 'Ps' as given by suction pressure transmitter [5].

$$qr^2 = \frac{\Delta Pos}{Ps} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

Surge Parameter (Ss) is the ratio of SLL flow value corresponding to current OP flow value and the current OP flow value itself as shown in Fig. 6. It will be less than one for stable operation and greater than one for unstable operation. [5]

$$Ss = \frac{q^2_{r,sll}}{q^2_{r,op}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

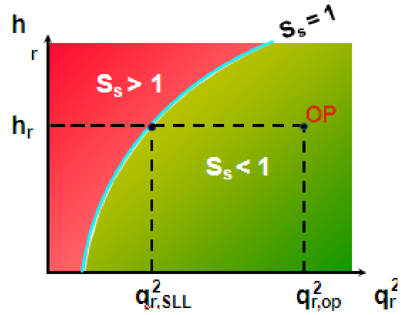

Figure 6. Surge Parameter 'Ss' Calculation [5]

Ss < 1	Stable operating zone
Ss= 1	Surge Limit Line (SLL)
Ss > 1	Surge region

Deviation parameter (DEV) is defined as [5]:

d = 1 – Ss………….………………6

DEV = d – surge margin = 1 – Ss – surge margin……7

Where surge margin is normally 10% additional margin for safety purpose. Its corresponding calculation is depicted in Fig. 7.

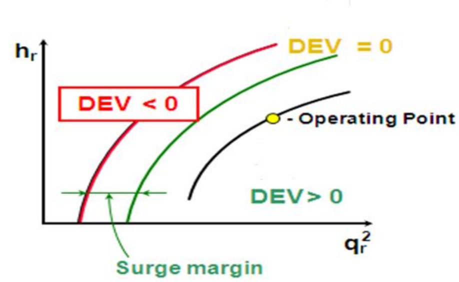

Figure 7. Deviation Parameter 'DEV' Calculation [5]

DEV > 0	Good
DEV = 0	Surge Control Line
DEV < 0	Bad

Hence, the main purpose of the algorithm is to determine the DEV parameter and to keep it positive.

PID Controller

The general control equation for a PID controller is given by [6]:

$$OP(t) = K_c E(t) + \frac{K_c}{T_i}\int E(t) + K_c T_d \frac{dE(t)}{dt} \quad \ldots\ldots 8$$

where:

OP(t) = controller output at time t

E(t) = error at time t

Kc= proportional gain

Ti= integral (reset) time

Td= derivative (rate) time

The stability of a system is a very important aspect to consider when designing control schemes. Improper tuning parameters can cause the oscillatory or even unstable response of a system. [6]

"Tuning" a control loop is a term used for optimum adjustment of PID controller parameters proportional gain Kc, Reset Time Ti, derivative time Td for the desired control response. There are several methods for tuning a PID loop e.g., "Ziegler-Nichols method", “Cohen- Coon Method” and “Hit and Trial Method” etc. Now-a-days, manual methods of tuning a PID controller are no longer used due to advancement of software technology. Many industrial softwares are now available which accurately model the process and then provide optimum values of these parameters for the user defined response. HYSYS has built-in PID controller tuning feature which is very beneficial for getting the proper tuning parameters with the facility of Online changing the parameters. [6]

Advanced Controller

In Advanced Controller, the control action is split into two actions: PI action and Recycle Trip action. [5]

PI action will deal with small and steady state disturbances while Recycle Trip Action will cope with sudden and quick process disturbances as depicted in Fig. 8. [5]

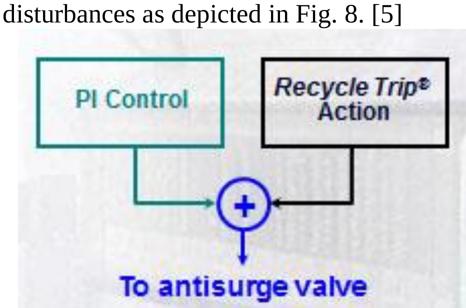

Figure 8. PI Plus Recycle Trip Response for Anti-surge Control Valve [5]

Two lines are introduced right to the SLL for this control algorithm: Surge Control Line (SCL) and Recycle Trip Line (RTL) as shown in Fig. 9.

PI action will be initiated when OP will touch the SCL while RTL-action will be activated by controller when OP will touch the RTL. RTL will generate an open loop response i.e., step opening response until the OP returns to the safe area. The magnitude of RTL response will be equal to the derivative of the surge parameter ‘Ss’ i.e., greater the rate of change, the greater will be the step response magnitude. [5]

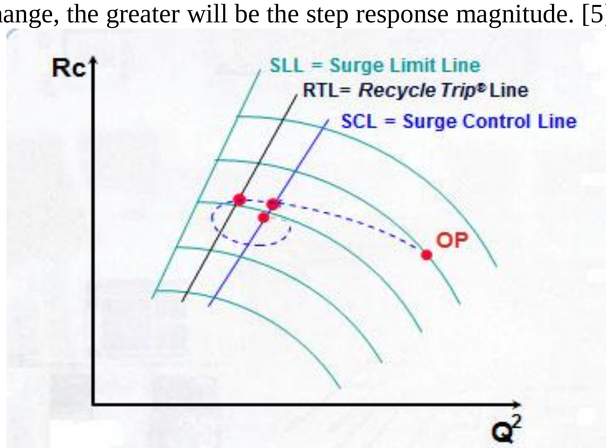

Figure 9. Surge Control Line (SCL) and Recycle Trip Line (RTL) [5]

Total response will be the sum of PI control response and Recycle Trip Response as shown in Fig. 10. [5]

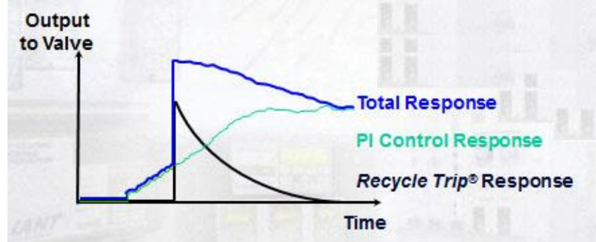

Figure 10. Output to Anti-surge Control Valve [5]

Please note that this derivative action (RTL) is separate from derivative action of a normal PID controller as this D-action is only concerned with opening of control valve whereas in a PID controller, derivative action takes part in both opening and closing of the valve. [5]

Methodology

Dynamic simulation of a centrifugal compressor was carried out in HYSYS. Surge conditions were simulated for high header pressure, low suction pressure, start-up and emergency shutdown of the unit. Conventional PID and Advanced (PI plus Recycle Trip) controllers were implemented to check their performance to protect the compressor from surge in different scenarios. The model of compression system implemented in HSYSY is shown in Fig. 11.

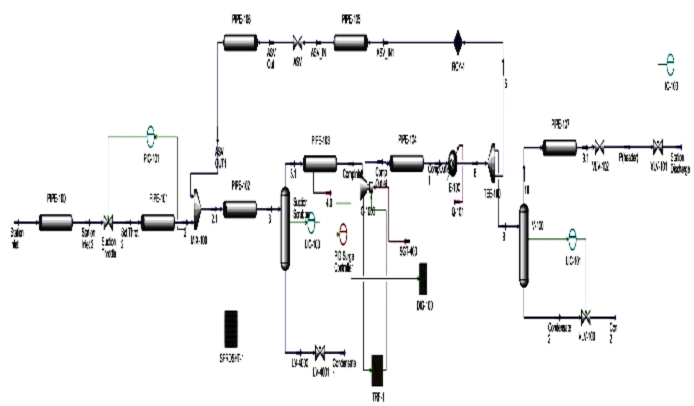

Figure 11. Model of Centrifugal Compressor Implemented in HYSYS

Model Validation:

The parameters for the centrifugal compressor, scrubbers, heat exchanger, control valves and piping were taken from Gas Compressor Station. Comparison between values obtained from HYSYS and actual values obtained from gas compressor station was carried out to check the validity of the model and great similarity was found. Table 1 shows the comparison of some important values obtained from field with those obtained from the model and are quite similar which validates our HYSYS model.

Table 1: Validation of HSYSY Model of Centrifugal Compressor Station

Parameter	Practical Value	HYSYS Value	Units
Suction Pressure, Ps	1538	1528	kPag
Suction Temperature, Ts	33.6	33.81	degC
Suction Flow, DeltaP	13.65	13.37	kPag
Discharge Pressure, Pd	2973	2925	kPag
Discharge Temperature, Td	98.9	88.27	degC
Compressor Speed	7746	7746	rpm
Suction Throttle	99.66	100	%
ASV Position	0	0	%

RESULTS AND DISCUSSIONS

Simulation of Surge Scenarios

System Parameters:
Rated (100 %) Speed of Turbo-compressor Unit = 9500 rpm
70 % (Minimum Governor) Speed of Turbo-compressor Unit= 6650 rpm
Surge limit Flow Level at 70% Speed = 5000 act_m3/hr
Surge Control Line Level (1.1 times Surge Limit Level) = 5500 act_m3/hr
RTL Response Level (6% from Surge Limit Level) = 5300 act_m3/hr
Note:
In this simulation, gas composition is assumed constant and simulation is carried out with fixed speed of centrifugal compressor which is the minimum governor speed i.e., 6650 rpm. Therefore, for simplicity, a flow based controller is implemented as surge controller taking input PV from compressor inlet and output is the anti-surge control valve. The controller maintains the flow at 1.1 times the surge flow at the given compressor speed through two ways discussed separately: simple PID control action and Advanced PI plus RTL action.
Surge Parameter at SLL = 1
Surge Parameter at SCL = 0.826
Deviation, DEV at SLL= -0.173
Deviation, DEV at SCL = 0
Hence, the safe range of surge parameter is less than 1 and safe range for DEV parameter is greater than -0.173.
The parameters incorporated for controllers are mentioned as under:
PID Controller Parameters:
Set Point = 5500 act_m3/hr
Gains: Kc = 0.3, Ti = 0.5 min / rep, Td = 0.083 min
In tuning the PID controller, assistance from HSYSY built-in PID Auto Tuning feature was taken for optimum, fast and stable response.
Advanced Controller Parameters:
Set Point = 5500 act_m3/hr
Gains: P = 0.5, Ti = 0.1 min /rep
RTL = Depends upon rate of change of Ss (10% optimum set in our simulation case. Greater than 10 % causes unstable response with hunting in ASV and less than 10 % causes slow response making system ineffective for fast surge protection.)

Case 1: Header Pressure > Discharge Pressure
Surge condition is simulated by closing the Discharge Valve VLV-100 in a quick manner to increase the header pressure for surge creation as shown in Fig. 12. As the header pressure is increased from 2447 kPag to 2720 kPag, the compressor goes into surge and flow starts fluctuating.

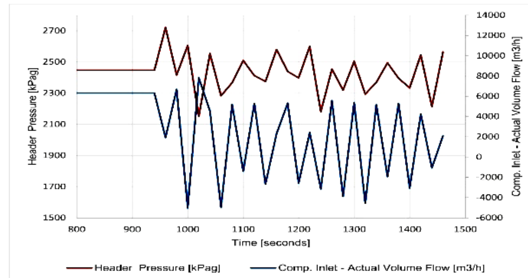

Figure 12. Surge Condition when Header Pressure > Discharge Pressure

Case 2: Low Suction Pressure
The surge condition for low suction pressure was simulated by closing the suction throttle valve in a quick manner as show in Fig. 13. As the suction pressure is reduced from 1520 kPag to 1200 kPag, the surge occurs and flow starts fluctuating first peak goes from 8564 m3/hr to -8107 m3/hr near 1500th second.

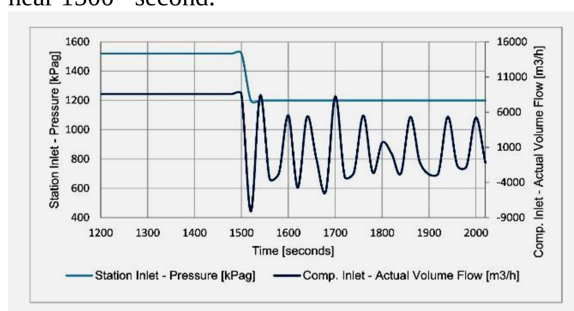

Figure 13. Surge Condition when Suction Pressure Decreases

Case 3: Start-Up of Unit
Surge condition during start-up of unit was simulated as shown in Fig. 14. Speed of turbo compressor unit is increased from 0 to 6650 rpm with closed ASV, surge occurs and flow fluctuates from -6258 to 8480 and further continues fluctuating making the system unstable.

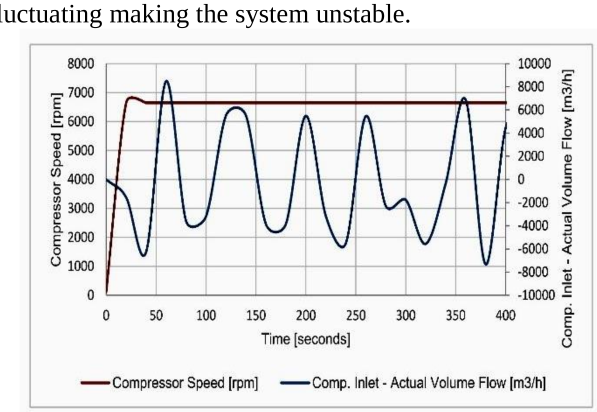

Figure 14. Surge Condition during Start-up of Unit

Case 4: Emergency Shutdown (ESD) of Unit

Surge condition during ESD of unit is shown in Fig. 15. As the unit shutdown was initiated, Suction throttle valve and Discharge valve Val-101 were fully closed with closed ASV and speed of the turbine was ramped down. When the speed decreases from 6650 rpm to 3325 rpm, flow reversal takes place from 8627 m3/hr to -3646 m3/hr. Thus the system experiences surge.

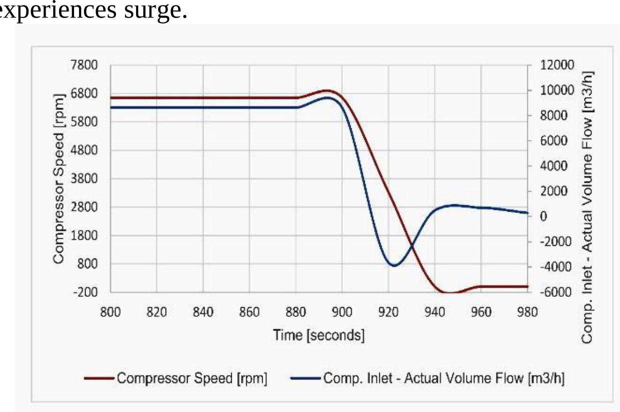

Figure 15. Surge Condition during ESD of Unit

Anti-Surge Controller Simulation Results

Case 1: Response of ASC when Surge Occurs due to High Header Pressure

Conventional PID Controller

When the header pressure is increased from 3281 kPag to 3548 kPag at 3100th second, the flow reduces to 5049 m3/hr, ASC generates output to open ASV to increase flow to the set point 5500 m3/hr as shown in Fig.16. The system does not experience surge in this case.

Surge parameter goes from 0.6 to 1.0 and DEV goes from 0.2 to -0.175 during low flow situation and restores to normal values after control action by ASV.

Limitations of PID Control Action

As the header pressure is increased from 3282 kPag to 3600 kPag at 5860th second in a quick manner to bring quick sever surge, ASC generates 25% output) to open ASV to restore flow but the flow reduces from 6235 m3/hr to 3299 m3/hr and the compressor goes into surge as shown in Fig. 17. After 02 cycles of surge, the system restores to the set point with 33 % output to ASV.

Surge parameter goes from 0.64 to 2.3 and DEV goes from 0.18 to -1.47 in this case. The compressor experiences surge.

Advanced PI Plus RTL Controller

When the header pressure is increased from 3284 kPag to 3619 kPag at 4920th second in a quick manner to bring sever surge, ASC generates 27% output (17% PI + 10% RTL)in a speedy manner to open ASV to restore flow and the flow reduces from 6250 m3/hr to 5213 m3/hr, then restores to 5500 m3/hr as shown in Fig. 18. The compressor is protected from surge.

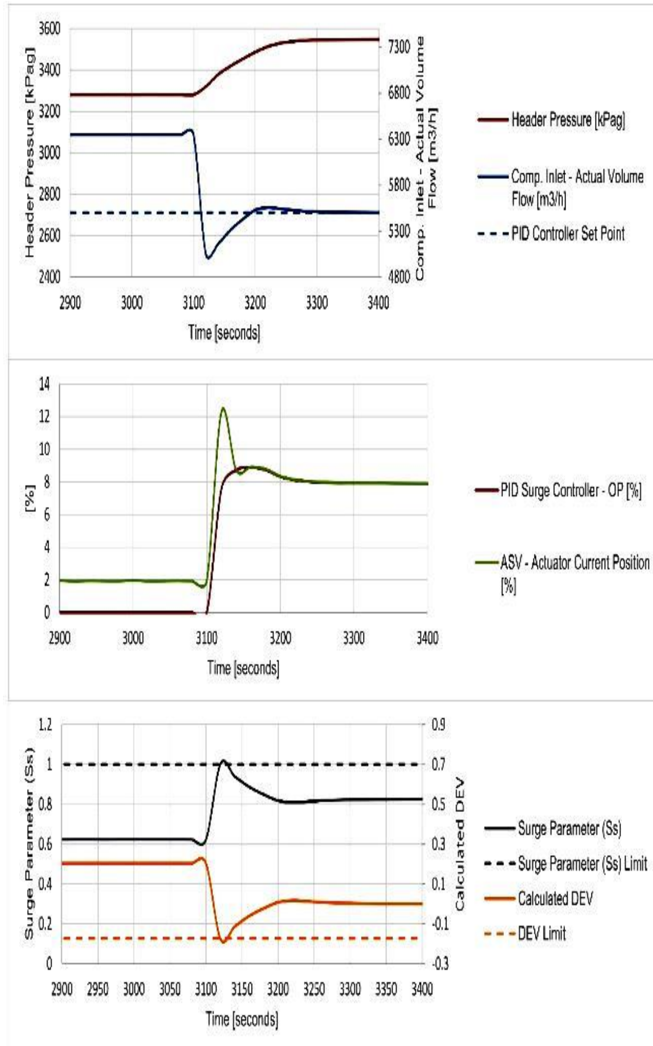

Figure 16. Conventional PID Controller Response for Surge Protection due to High Header Pressure

Surge parameter goes from 0.64 to 0.92 and DEV goes from 0.18 to -0.05, not crossing the limits, thus the system remains stable. Advanced PI plus RTL response is superior in performance and protection of centrifugal compressor.

Case 2: Response of ASC when Surge Occurs due to Low Suction Pressure

Conventional PID Controller

As the suction pressure is decreased from 1827 kPag to 1686 kPag at 9140th second, the flow reduces from 6279 m3/hr to 5406 m3/hr, ASC generates 7% output to open ASV to restore flow to the set point 5500 m3/hr as shown in Fig. 19.

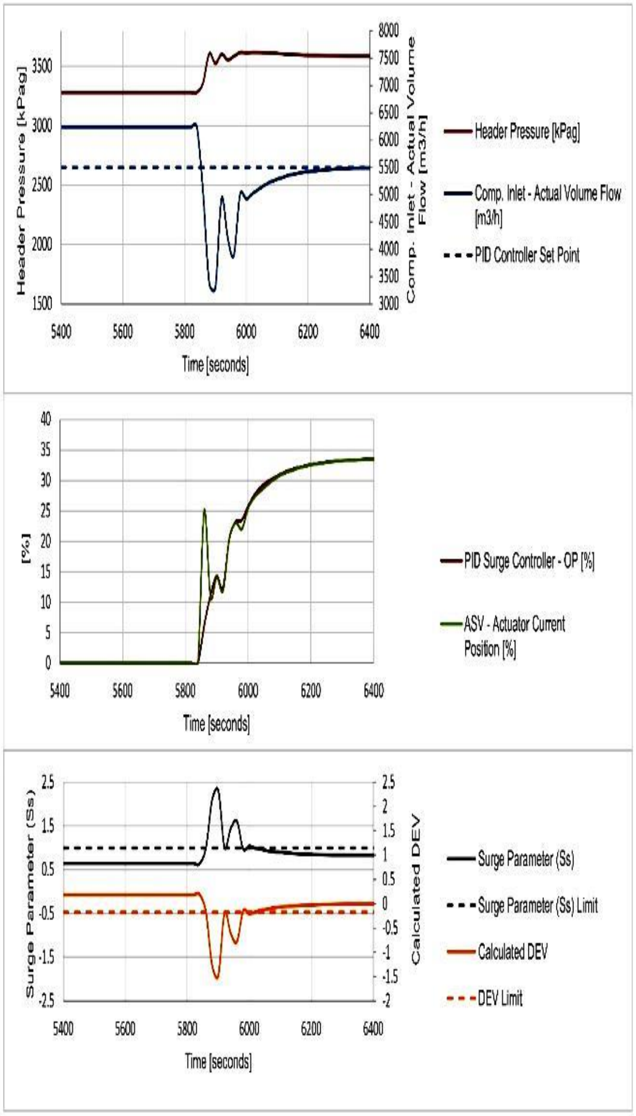

Figure 17. Limitation of Conventional PID Controller for Sever Surge Case due to High Header Pressure

Surge parameter goes from 0.63 to 0.85 and DEV goes from 0.19 to -0.02 as shown in Fig. 19.

Limitation of Conventional PID Controller

As the suction pressure is decreased from 1824 kPag to 1650 kPag at 9500th second in a quick manner to bring sever surge, ASC generates 30% output to open ASV to restore flow but the flow reduces from 6319 m3/hr to 3580 m3/hr and the compressor goes into surge as shown in Fig. 20. After 01 cycle of surge the system restores to the set point with 33 % output to ASV.

Surge parameter goes from 0.625 to 1.97 and DEV goes from 0.2 to -1.15 as shown in Fig. 20.

Advanced PI Plus RTL Controller

As the suction pressure is decreased from 1825 kPag to 1656 kPag at 7520th second in a quick manner to bring sever surge, ASC generates 35% output (25% PI + 10% RTL) in a speedy manner to open ASV to restore flow and the flow

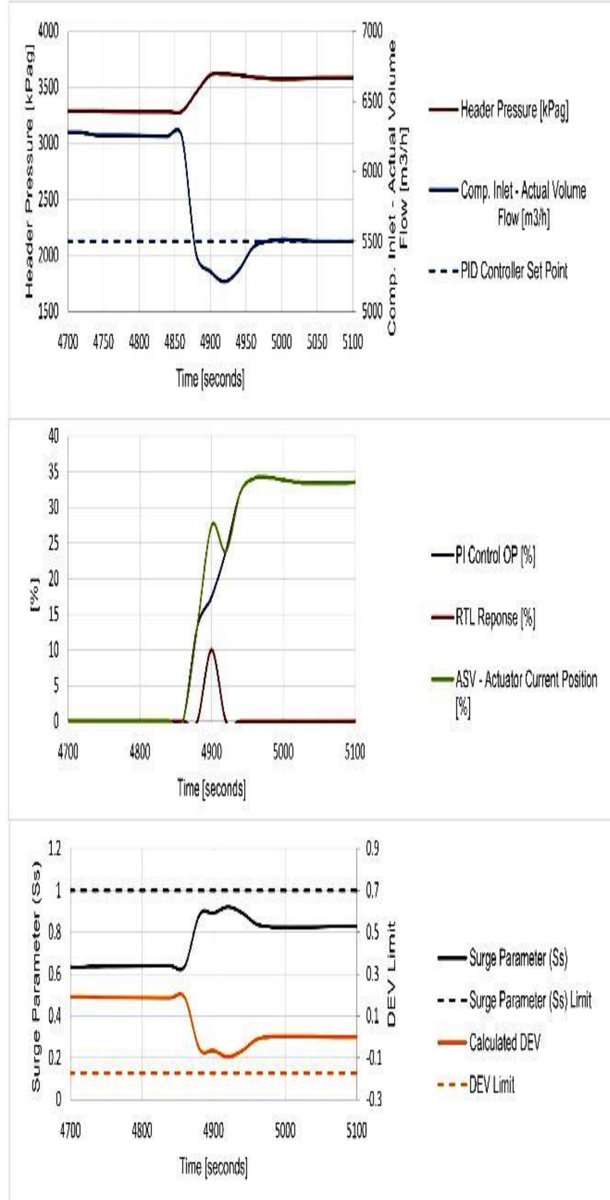

Figure 18: Advanced PI + Recycle Trip Controller Response for Sever Surge Case due to High Header Pressure

reduces from 6320 m3/hr to 5071 m3/hr, then restores to the set point 5500 m3/hr as shown in Fig. 21. The compressor is protected from surge.

Response for Sever Surge Case due to Low Suction Pressure for Sever Surge Case due to Low Suction Pressure

Surge parameter goes from 0.625 to 0.97 and DEV goes from 0.2 to -0.15, then restores to the normal values and the system remains stable as shown in Fig

Case-3: Protection from Surge during Start-up

ASV remain fully open as the speed of the turbine compressor unit is increase from 0 rpm to 6650 rpm in 60seconds, the flow increases to maximum value 8681 m3/hr and then becomes smooth at 8627 m3/hr as shown in Fig. 22. No surge occurs in this case.

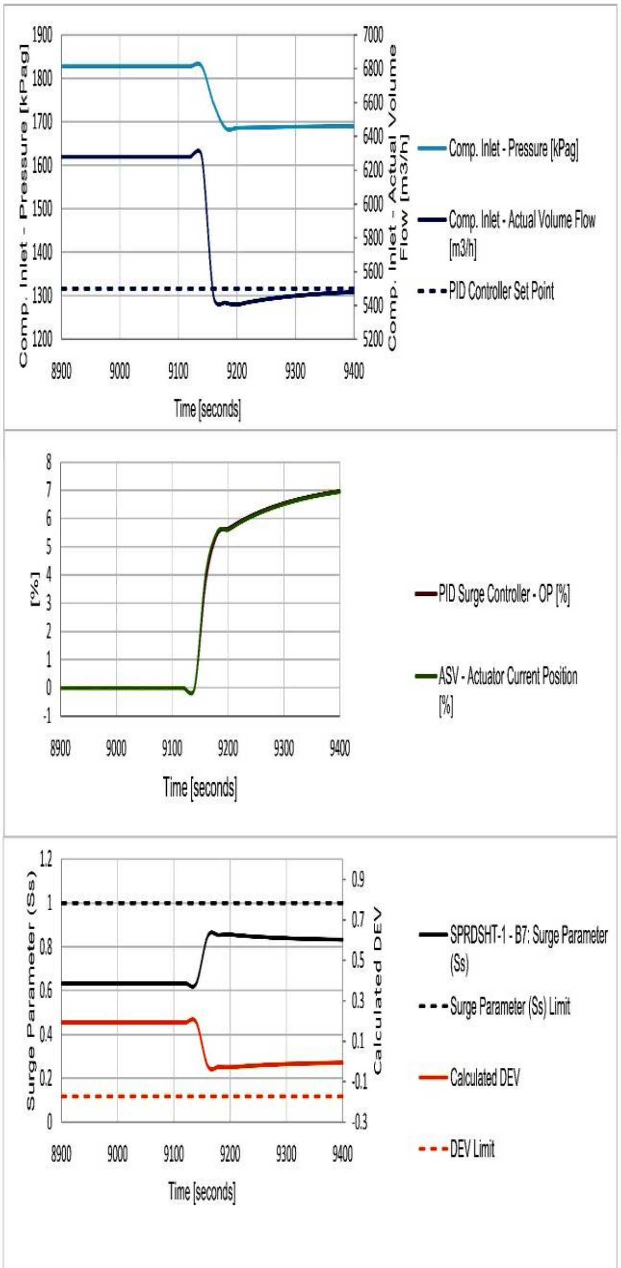

Figure 19. Conventional PID Controller Response for Low Suction Pressure Surge

Case-4: Protection from Surge during Shut-down of Unit

As ESD command initiated, ASV fully opens and the speed of the turbine compressor unit decrease to 0 rpm from 6650 rpm to 0 rpm, the flow decreases in line with the speed as shown in fig 23. No surge occurs in this case.

CONCLUSION:

Anti-surge valve and Anti surge controller plays an important role in the protection of centrifugal compressor from surge. Surge is a speedy phenomenon, can occur during start-up, emergency shutdown, high header pressure and low suction pressure as explored in this study. Properly tuned conventional PID controllers become ineffective when severe surge occurs in a very less time, thus advanced control becomes necessary. Advanced controller generates PI response and a quick opening open loop response called as recycle trip response which gives sudden opening to ASV when RTL threshold is crossed. Advanced controller works well in sever surge case and protects the compressor from surge effectively. ASV should be opened fully during start-up and ESD of the unit to protect from surge

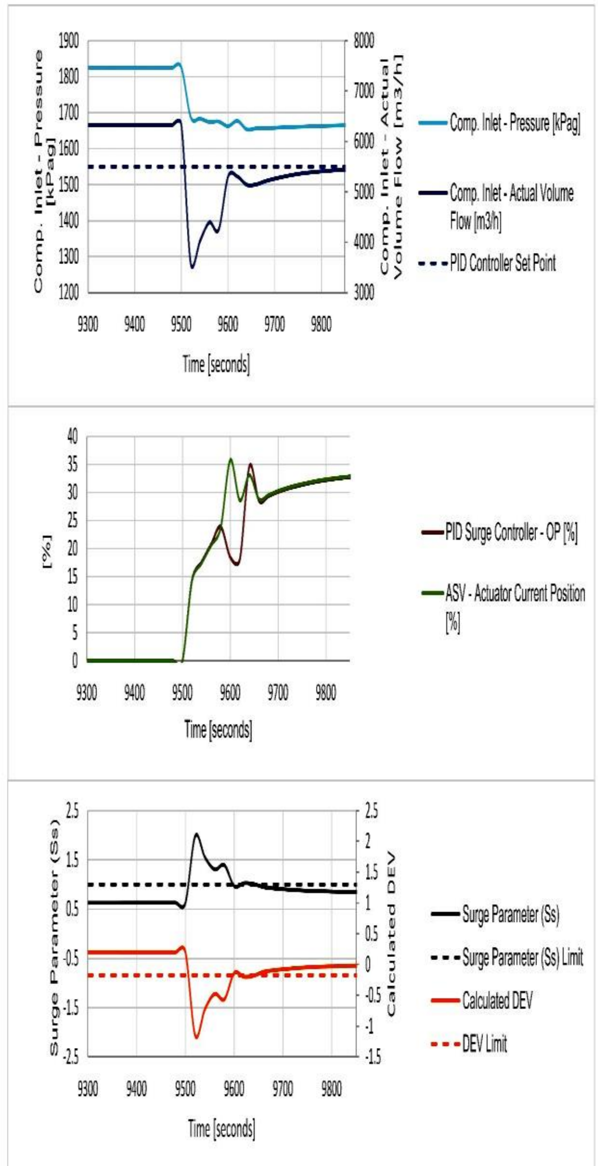

Figure 20. Limitation of Conventional PID Controller

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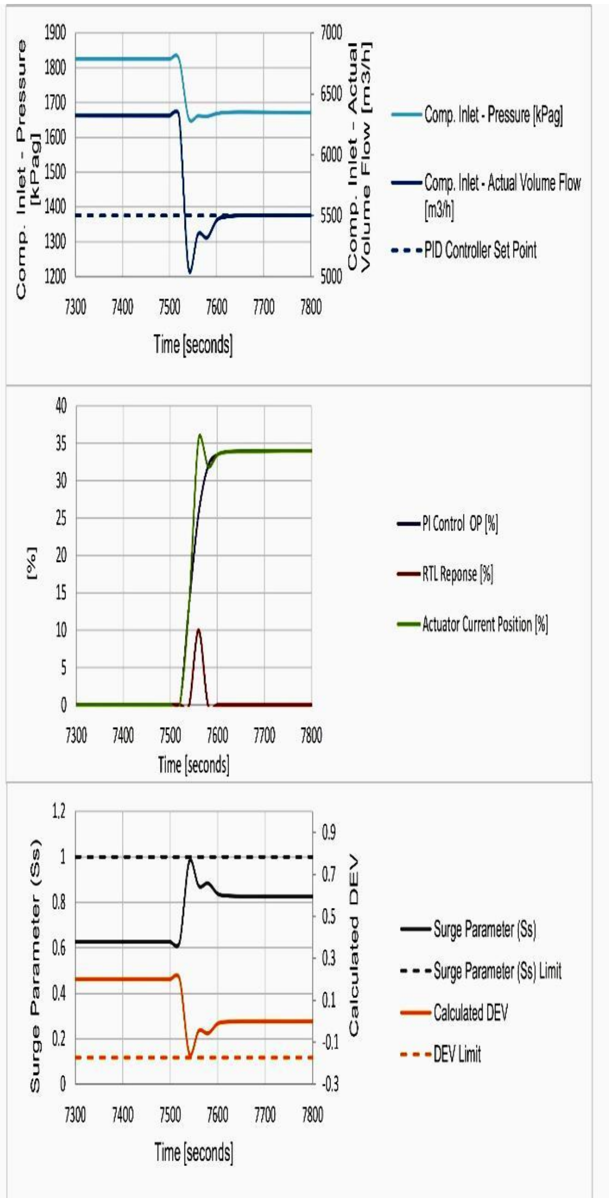

Figure 21. Advanced PI + Recycle Trip Controller Response

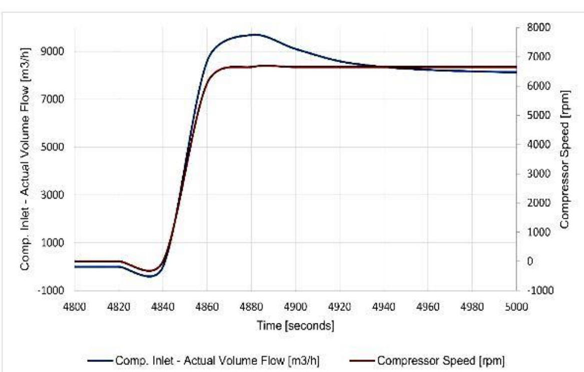

Figure 22. Protection from Surge during Start-up of Unit

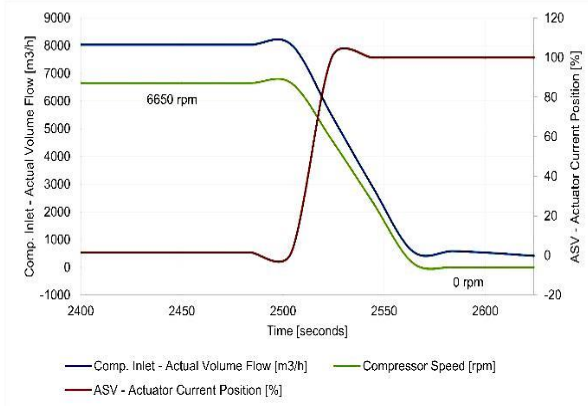

Figure 23. Protection from surge during ESD of Unit

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