Benefits of High-Fidelity Dynamic Simulation

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ABSTRACT

The use of high-fidelity dynamic simulation (HFDS) offers numerous benefits throughout the process lifecycle. The primary areas of benefit include better equipment sizing and selection, optimum control design, reduced errors, cost and time savings, and improved safety and training.

Process and control design may benefit from HFDS. Process equipment may be sized and selected to meet not only capacity and cost but also transient requirements. For example, a high-fidelity control valve model may help size and select the valve and avoid problems such as oversizing and poor dynamic performance. A high-fidelity control valve model is often critical in tuning flow or pressure controllers in the simulation system and then applying the results directly to its real system. HFDS is important in developing and evaluating advanced process controls (APCs) at design stage to avoid poor-performing APCs in an actual plant. Tuning PID and APC controllers on high-fidelity dynamic simulation prior to commissioning the system saves time and cost.

HFDS simulates behaviors and performance not only under normal conditions but also during startup, shutdown and abnormal conditions. Therefore it can be used to check out and verify that individual equipment and the overall system will perform as designed, thereby minimizing costly design errors. Designers can use the simulation to verify process control strategy and operation procedures during abnormal events such as equipment malfunctions and process disturbances. It is a powerful tool for training operators to handle various normal and abnormal operating conditions.

HFDS may be one of most effective tools in trouble-shooting an existing control performance problem and finding an optimum solution. By comparing field data with simulation data, model parameters such as valve frictions and heat exchanger fouling resistance may be updated to match field data to repeat the behaviors. Various what-if scenarios can be explored in the simulation runs to understand problems and find solutions.

INTRODUCTION

Steady-state simulations are widely used in process design today. Increasing energy cost and strict environmental protection have led to more energy integration and stream recycling throughout process plants, requiring more sophisticated control and startup procedures. Dynamic simulation is increasingly applied as one of the tools to face the challenges in the process industry. HFDS can be applied for many purposes from sizing equipments, developing control strategies, obtaining process dynamic models, tuning controllers to training operators and engineers.

Many industrial processes are complicated and highly nonlinear. Simplification and linearization in equipment and process modeling and simulation may produce inaccurate results that are misleading and cause design failures. The black box dynamic models developed by system identification techniques may describe systems well in specific operating conditions, but model accuracies may be degraded to unacceptable levels when operating conditions change. High-fidelity dynamic modeling based on first-principle is potentially capable of covering wide operating ranges. It is also natural to integrate steady-state and dynamic simulation into the same environment in order to build a virtual system as if building a real plant, using pre-built equipment, instrument and controller blocks. This would allow beneficial interactions between process design and control design and increase the efficiency in building HFDS.

APCs are increasingly used in the process industry to improve control performance. These APC controllers may bring little or significant benefits depending on specific applications. Even if the application is appropriate for an APC controller, poor implementation and maintenance may result in an underperforming APC control system. High-fidelity dynamic models are useful for feasibility studies, model identifications, tuning, verification, validation and maintenance of APC controllers.

EQUIPMENT SIZING

Dynamic performance is difficult to quantify in individual equipment sizing. Even in the specification sheet of a control valve or an intermediate buffer tank, there is hardly any data directly related to dynamic performance. HFDS based on first-principle is an effective tool in demonstrating the relationships among dynamic behavior, individual equipment data and process fluids. Thus, the dynamic simulation can help size the equipment based not only on purchase and operation costs, capacity, temperature and pressure rating, fluid compatibility and other process requirement, but also on overall dynamic performance.

Figure 1 is an example how control valve friction may affect the resolution of a control valve. Valve A is a 2-inch valve with low friction packing while valve B is a valve with high friction packing. Both sliding-stem post guiding globe valves are equipped with the same type of smart positioners. In a flow control simulation, the low friction valve A demonstrates a better flow resolution than valve B. A higher flow resolution can achieve more precise control and reduce valve wearing and instrument air consumption.

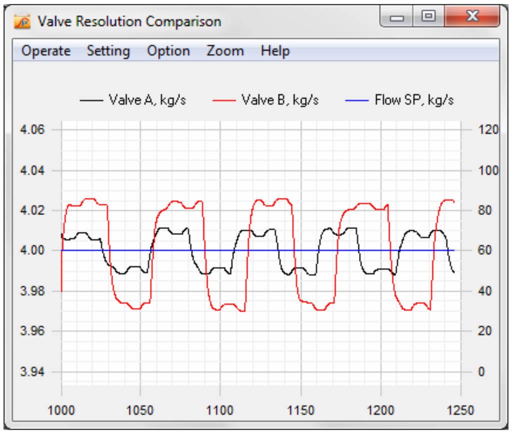


Fig. 1. Control valve resolution comparison.

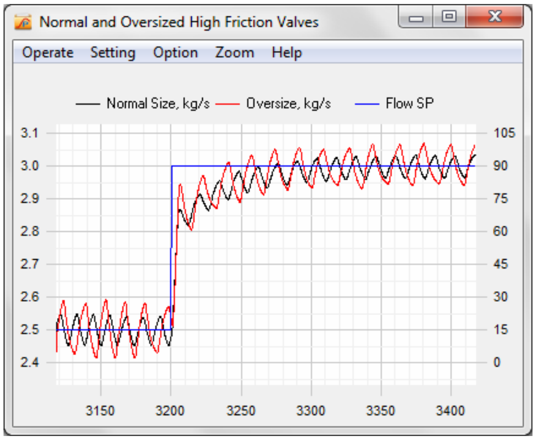


Fig. 2. Normal and oversized high friction valves

During process design, safety margins are added in the sizing of equipment such as pumps, compressors and valves. As a result many control valves are oversized and positioned significantly lower than typical desirable travel range in normal operating condition. An oversized valve has excessive flow capacity and costs more if the excessive capacity commands a larger valve body. It can affect control performance negatively, especially when the valve friction is high. Figure 2 shows how high packing friction effect is amplified in the oversized valve with graphite packing for the same flow control application. A rotary valve may have significant shaft windup when seating and may have a significant dead zone especially if an equal percentage characterizer is applied.

A control valve has linear, equal-percentage, quick opening or modified-flow characteristics. Valve inherent characteristic selection is important because it is used to compensate process nonlinearities or accommodate process requirements. When valves are installed with pumps, compressors, piping and fittings, and other process equipment such as heat exchangers, the pressure drop across the valve will vary as the valve plug moves through its travel. Valve installed flow characteristic may be obtained from

HFDS as illustrated in Figure 3. Though the inherent equal percentage characteristic (red curve) of valve trim is the right choice for this application, there is still a significant nonlinearity in the installed flow characteristic (black curve). From the slope of the black curve, we can see large flow gains between 50 and 70% of valve travel and small flow gain over 80% travel. The flow control test demonstrates the flow gain nonlinearity in Figure 4. At low and high flow rates, flow rate step responses are slow. At medium flow rate, step responses are fast with significant overshoots. To help achieve better flow control, a signal characterization block can be configured with characteristic of the inverse of the process gain. The characterizer can be a block between the controller and the control valve or located inside a smart positioner (software function block) or in a pneumatic positioner (a mechanical cam). Without high-fidelity simulation, it may become a safety risk in the field to stroke a control valve from fully closed to fully open to find installed characteristic.

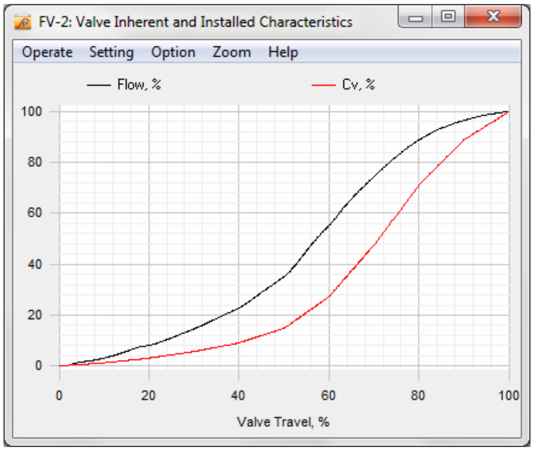


Fig. 3. Valve inherent and installed characteristics.

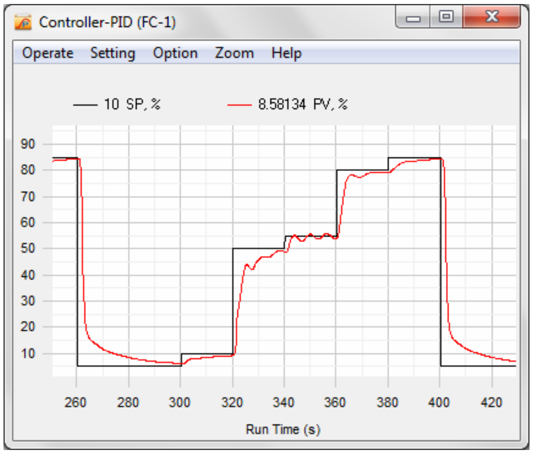


Fig. 4. Flow control nonlinearity test.

The high-fidelity simulation will show valve positions and pressure drops across control valves at different operating conditions, so the oversized and undersized valves can be easily exposed and replaced at the design stage. Note that pressure drop data across a valve may not be accurate during the preliminary control valve sizing. In addition, potential control performance problem can be identified. With HFDS, equipment such as control valve and buffer tank may be sized based on cost and overall performance.

EVALUATING ALTERNATIVES

During the process and control design, there are always many choices to make. HFDS is an effective tool you can apply to evaluate alternatives and find optimum solutions. Examples include globe valve versus a rotary valve, PI-D versus I-PD algorithms, variable frequency drive (VFD)-based centrifugal pump versus control valve, PID versus MPC controllers, shell and tube versus spiral heat exchangers, and trayed versus packed columns. HFDS can offers great flexibility and useful data to the user in evaluation. For instance, you may copy and paste the entire system on the same flowsheet, make any change you want and run it so direct comparison can be made during the simulation run.

Valve signature (actuator versus position) test results and 1% position step change responses using high-fidelity control valve models are shown in Figures 5 to 8 for relatively low and high friciton control valves. A control valve cannot move (stick) until it accumulates enough actuator forces to overcome its static friction. When it moves it may travel more than needed (slip) because lower dynamic friction. So valve friction affect both valve resolution and dynamic responses. High friction causes valve response delay especially at small changes that may result in process cycling (Figure 2).

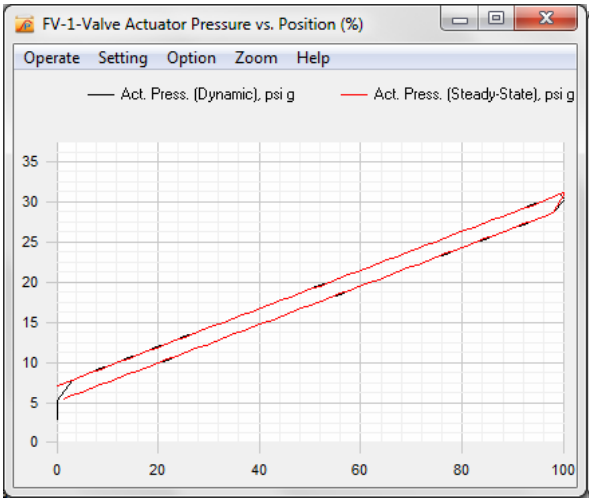


Fig. 5. Low friction valve signature

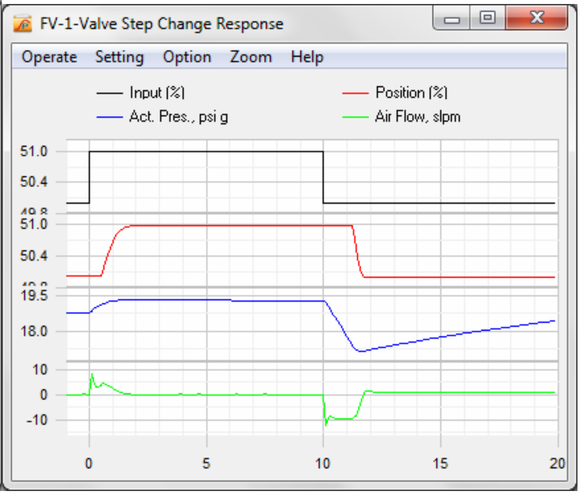


Fig. 6. 1% travel step response of low friction valve

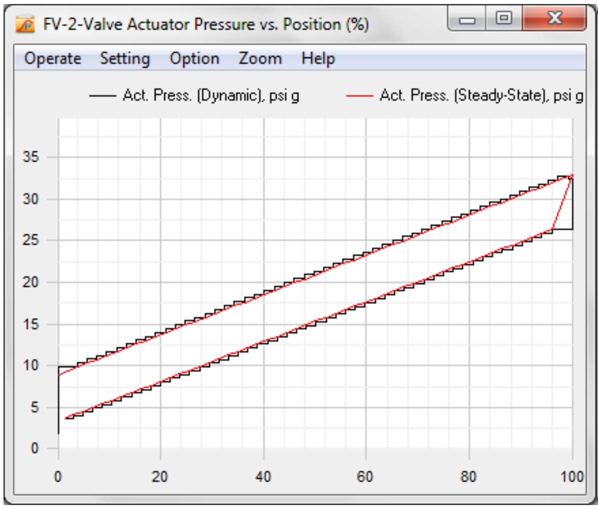


Fig. 7. High friction valve signature

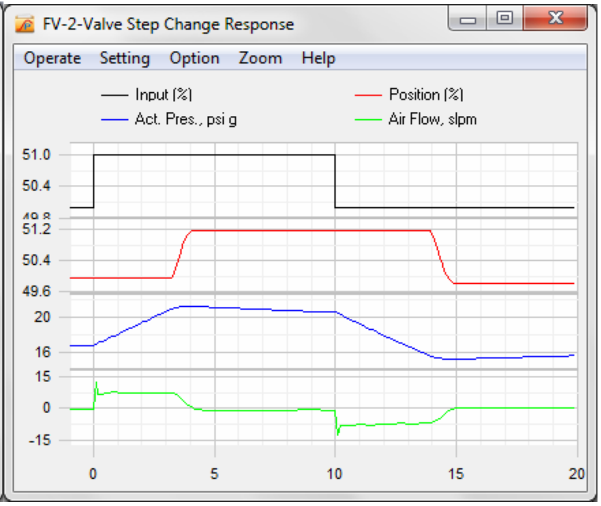


Fig. 8. 1% travel step response of high friction valve

There are many factors that need to be considered when evaluating a VFD pump versus a control valve for flow control application. These include flow control, VFD driver cost (purchase, installation and maintenance), harmonic distortion from VFD, flow shut-off requirement, electricity cost saving, and fugitive emissions or packing leakage from the control valve. HFDS can evaluate many of the factors including cost saving and flow control performance and assist in the decision making. Figures 9 to 11 shows how a VFD pump may reduce annual electricity cost from $7381.65 down to $2489.94 and improve the resolution and dynamics of flow control for a particular application.

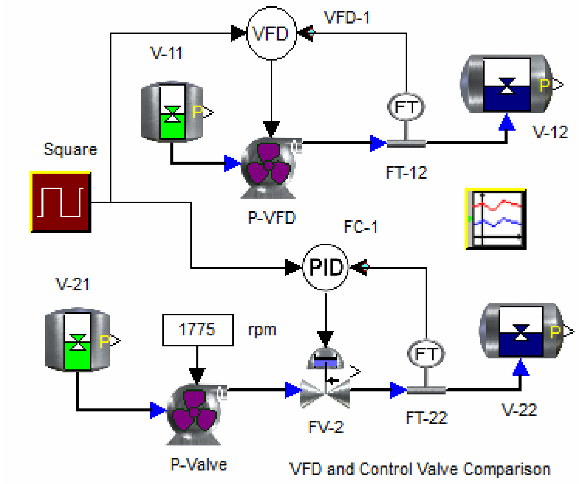


Fig. 9. VFD based pump versus control valve simulation.

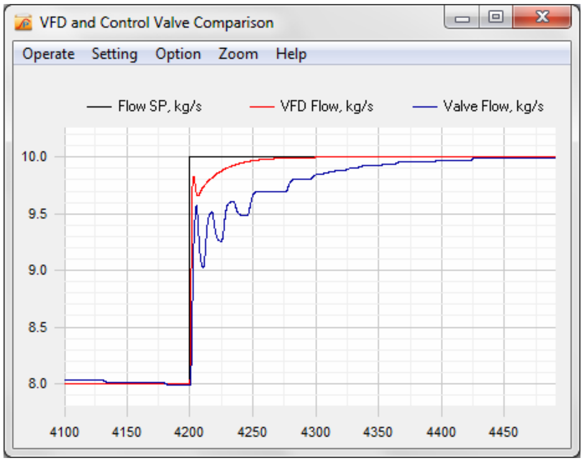
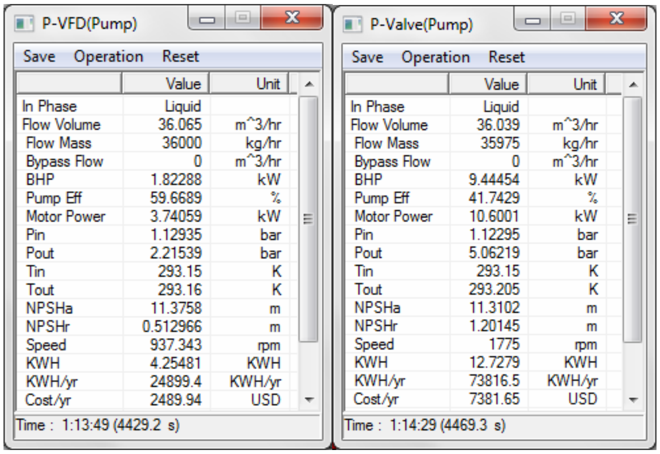


Fig. 10. Flow control: VFD pump versus control valve



	Value	Unit
In Phase	Liquid	
Flow Volume	36.065	m^3/hr
Flow Mass	36000	kg/hr
Bypass Flow	0	m^3/hr
BHP	1.82288	kW
Pump Eff	59.6689	%
Motor Power	3.74059	kW
Pin	1.12935	bar
Pout	2.21539	bar
Tin	293.15	K
Tout	293.16	K
NPSHa	11.3758	m
NPSHr	0.512966	m
Speed	937.343	rpm
KWH	4.25481	KWH
KWH/yr	24899.4	KWH/yr
Cost/yr	2489.94	USD

Time : 1:13:49 (4429.2 s)

	Value	Unit
In Phase	Liquid	
Flow Volume	36.039	m^3/hr
Flow Mass	35975	kg/hr
Bypass Flow	0	m^3/hr
BHP	9.44454	kW
Pump Eff	41.7429	%
Motor Power	10.6001	kW
Pin	1.12295	bar
Pout	5.06219	bar
Tin	293.15	K
Tout	293.205	K
NPSHa	11.3102	m
NPSHr	1.20145	m
Speed	1775	rpm
KWH	12.7279	KWH
KWH/yr	73816.5	KWH/yr
Cost/yr	7381.65	USD

Time : 1:14:29 (4469.3 s)

Fig. 11. VFD based pump versus fixed speed pump.

MODELING AND CONTROLLER TUNING

One of the most important goals to using HFDS is that controller tuning parameters based on simulation may be applied to the controllers used for the actual process. High-fidelity equipment modeling is a very basic necessity for building HFDS. For common liquid flow and pressure control loops, control valve dynamics are dominating with various nonlinear behavior such as nonlinear installed characteristic (gain), limited resolution, stick-slip movement, asymmetric travel responses, travel velocity limits and dead band. Therefore the high-fidelity modeling of control valves is critical for describing the system and the tuning of flow and pressure controllers. A pneumatic control valve system consists of a valve body, an actuator and positioner or I/P converter with optional airset and air booster. All these components need to be modeled accurately. Interaction among these components and the process fluid passing through must be modeled precisely so they can act accurately in the simulation.

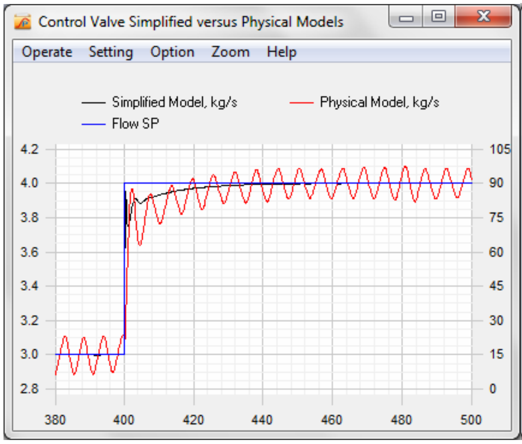


Fig. 12. Simplified and Physical Valve Models

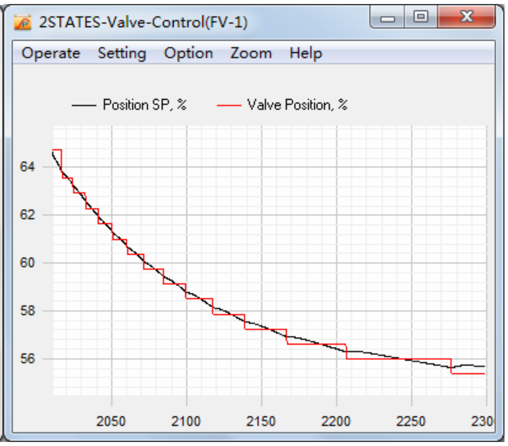


Fig. 13. High friction valve exhibits stick-slip behavior

Figure 12 plots flow step responses of a dynamically simplified control valve and high-fidelity control valve in simulation run. There is no valve friction in the simplified control valve model and the flow controller gain can be mistakenly set much higher (2.0) without causing oscillations. However this valve has significant packing friction and exhibit stick-slip valve movement in the simulation (Figure 13) if the high-fidelity model is used. The stick-slip valve movement causes flow cycling and controller tuning alone is not effective to deal with the problem. It is better to address the problem at the design stage with viable alternatives.

Model identification is important for control design such as feedforword control, inferential control and model based control. Model based control cannot produce optimum results unless its internal model works properly over operating conditions. With HFDS, you may conduct all kinds of steady-state and dynamic tests to learn the behaviors and characteristics of a system without considerable risks of production loss, accidental shutdown, equipment damage and unexpected disturbances and failures. Test design and data from test signal selection such as step change or PRBS, and signal amplitude and test time learned from the modeling and tuning on the virtual process are valuable and can also be applied to the actual process to minimize test time and obtain the optimum results. Whenever possible, some equipment models should be validated and updated by actual operating data. Valve packing friction may change significantly in service. This may be identified by smart valve positioners. Flow and pressure data can be used to detect valve and pump inherent characteristic shifting. Heat exchanger fouling resistances can be estimated from inlet and outlet temperature reading.

Simple models such as one-order and two-order lag plus time delay are commonly used for PID open loop tuning. These models are also used as APC internal models. You can run model identification test on HFDS and fit data to obtain these simple models. Temperature response curves are plotted in Figure 15 based on simulation test data and model fitting from flow rate step change testing. The simple three-parameter model with gain of 0.287, time constant of 71.43 seconds and time delay of 18 seconds are used as an internal model for MPC. A larger overshoot is observed with PID controller at lower setpoint at 40 degree C (Figure 16). This nonlinearity is typical for heat exchanger temperature control systems without proper process gain compensation. Ignoring process nonlinearities in control design, the control performance may vary significantly with different operating conditions no matter what type of controller is used and how they are tuned.

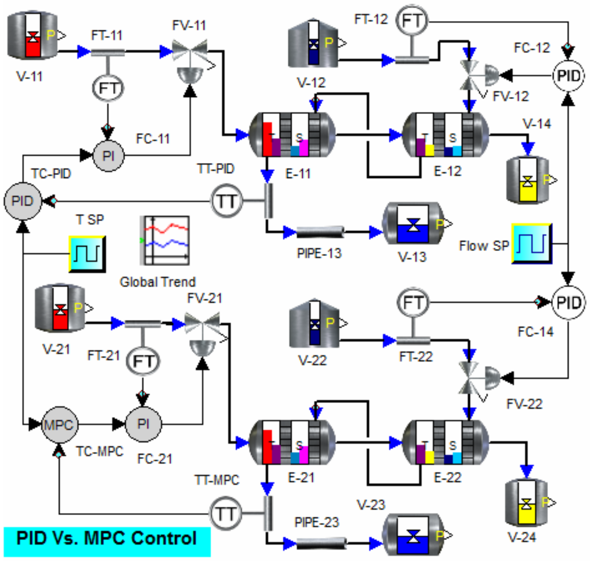


Fig. 14. PID versus MPC temperature control

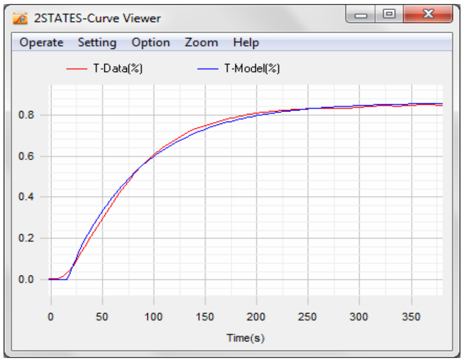


Fig. 15. Step change response and model fitting

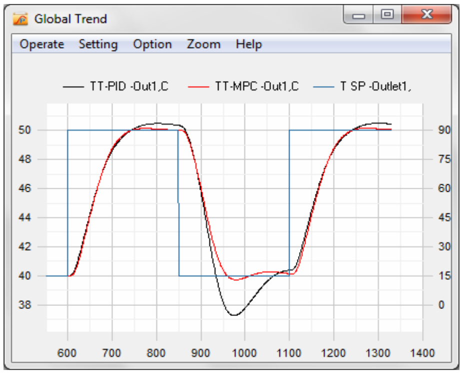


Fig. 16. PID versus MPC at SP change

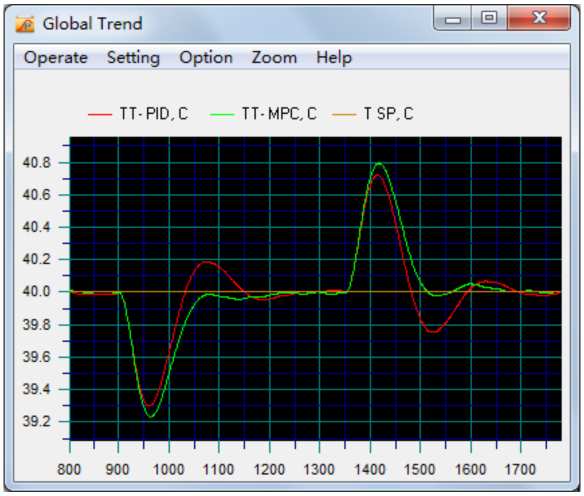


Fig. 17. PID vs MPC at load step change (high load)

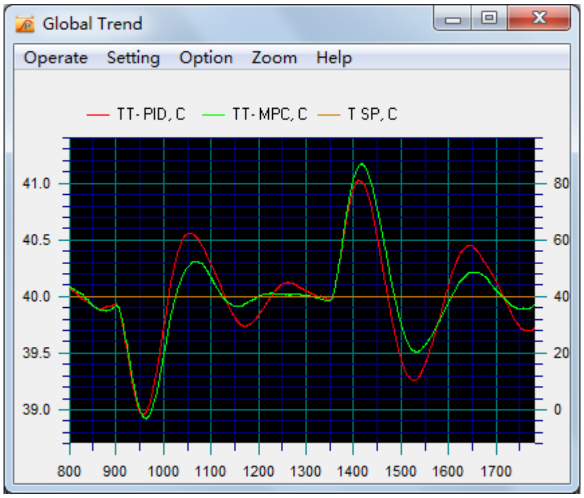


Fig. 18. PID vs MPC at load step change (medium load)

HFDS can help you identify the problem and find the best solution. Figure 17 shows PID versus MPC response at loads toggling between 80 and 90%. Because the MPC internal model is obtained based on testing data at 80% load, MPC control performance is degraded significantly at lower loads as shown in Figure 18 (loads toggling betweem 60 and 70%).

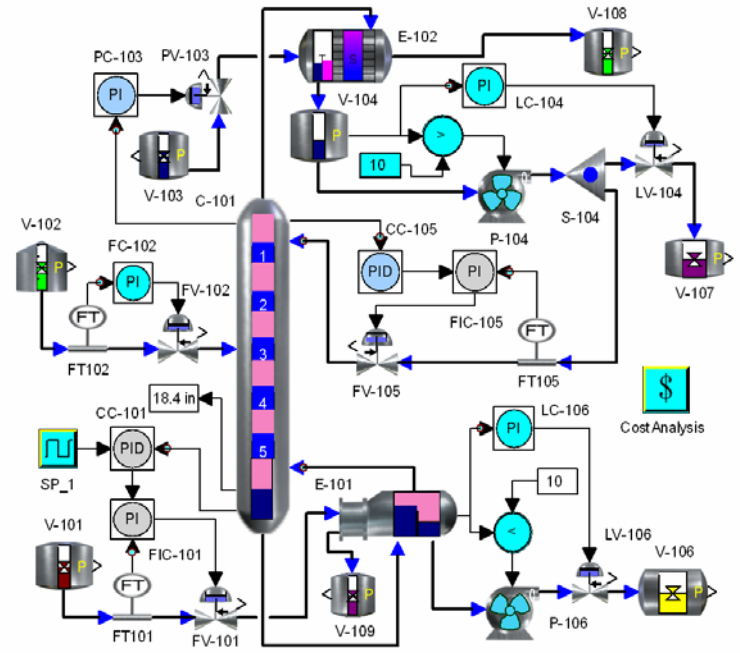


Fig. 19. Column dynamic simulation and PID closed-loop tuning

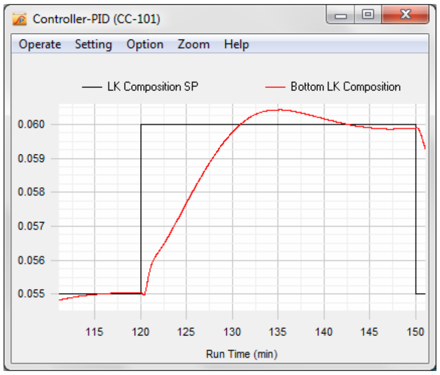


Fig. 20. Step response with Ti = 2 min

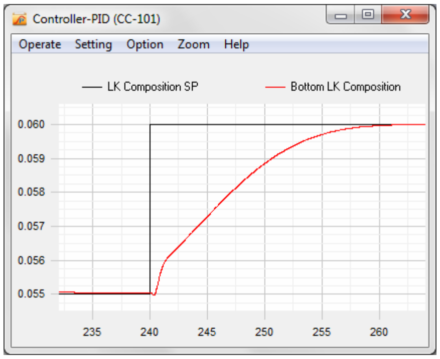


Fig. 21. Step response with Ti = 3 min

Tuning PID and MPC controllers on HFDS prior to commissioning can save time and cost. Tuning results can be applied to configure controllers and shorten the time between the commissioning and startup of a new plant. You can focus on the control loops that are needed to refine the tuning in real plants.

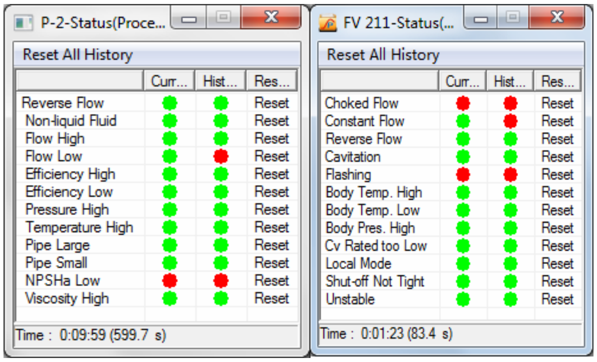
Closed-loop tuning on HFDS provide attractive alternatives to obtaining control parameters. You may bump the process at the level suitable for tuning and testing and ignore the consequences for safety or production loss. Figures 20 and 21 displays two snap shots of transient response of column bottom light key (LK) composition on its setpoint step change during the PID closed loop tuning. The trend in Figure 20 corresponds to PID integral time of 2 minutes while Figure 21 to integral time of 3 minutes. The PID parameter set with integral time of 2 minutes gives fast response with overshoot, while the other PID tuning brings a slower but smoother response. You can focus on learning and improving controller tuning by trial and error on HFDS. You do not need to worry about unexpected disturbances during the test that bring additional uncertainty to your test data. You can explore new ideas and options to achieve optimum results without the strict limitation you would experience working in a real plant.

DESIGN VERIFICATION

You can run HFDS under various normal and abnormal operating conditions. HFDS produces much more data than any modern data acquisition systems can collect. The simulation data can be used for design verification and model validation when field operation data are available. Because of that and the ability to simulate under various conditions such as equipment malfunctions , high-fidelity HFDS can be used as an operator training and decision support tool.

During a simulation, HFDS may provide functions to manipulate a process and produce information about process and control. Changes or disturbances can be scheduled automatically with built-in functions or blocks, or added manually at any time. These changes include but are not limited to production rates, feed composition, temperature or pressure, PID parameters, controller auto/manual transfer, control valve position, valve on/off, and pump/compressor/fan start/stop. Information generated in simulation includes fluid stream data, valve friction and noise, mismatch of piping and control valve sizes, instability such as limit cycling, valve tight shut-off, choked flow, equipment status, utilities usage and operation profitability.

A process plant is not operated only under rated conditions. Even seemingly perfect designs may not guarantee that there are no problems when the plant is placed in operation. Some problems can only be exposed under very specific conditions. Simulation runs from startup to shutdown and during abnormal conditions may expose some of design deficiencies and provide opportunities for further improvement on operation procedures. An extensive simulation run may help uncover oversized or undersized equipment, unexpected cavitations and flashing inside valves or pumps, excessive valve noises, abnormal reverse flows, insufficient valve seating forces to prevent tight shutoff, or column weeping and flooding, etc. It is also possible to check if there are any mismatches and conflicts in configuration and calibration among equipments, instruments and controllers, unstable and under performing control loops. So beneficial changes or improvement can be made at the design stage.



	Curr...	Hist...	Res...
Reverse Flow	🟢	🟢	Reset
Non-liquid Fluid	🟢	🟢	Reset
Flow High	🟢	🟢	Reset
Flow Low	🟢	🔴	Reset
Efficiency High	🟢	🟢	Reset
Efficiency Low	🟢	🟢	Reset
Pressure High	🟢	🟢	Reset
Temperature High	🟢	🟢	Reset
Pipe Large	🟢	🟢	Reset
Pipe Small	🟢	🟢	Reset
NPSHa Low	🔴	🔴	Reset
Viscosity High	🟢	🟢	Reset

Time : 0:09:59 (599.7 s)

	Curr...	Hist...	Res...
Choked Flow	🔴	🔴	Reset
Constant Flow	🟢	🔴	Reset
Reverse Flow	🟢	🟢	Reset
Cavitation	🟢	🟢	Reset
Flashing	🔴	🔴	Reset
Body Temp. High	🟢	🟢	Reset
Body Temp. Low	🟢	🟢	Reset
Body Pres. High	🟢	🟢	Reset
Cv Rated too Low	🟢	🟢	Reset
Local Mode	🟢	🟢	Reset
Shut-off Not Tight	🟢	🟢	Reset
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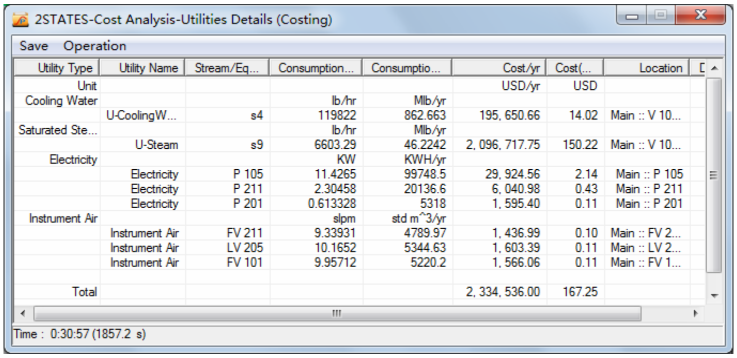


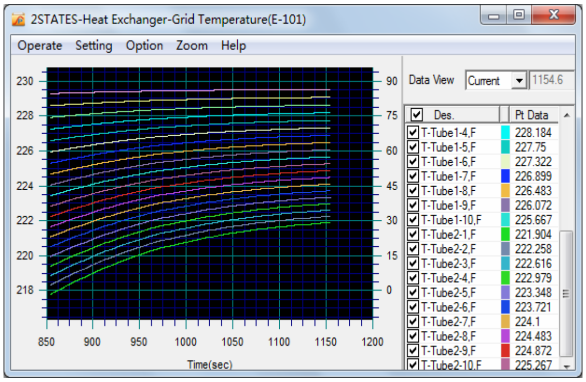
Utility Type	Utility Name	Stream/Eq...	Consumption...	Consumptio...	Cost/yr	Cost(...	Location
Unit					USD/yr	USD	
Cooling Water			lb/hr	Mlb/yr			
	U-CoolingW...	s4	119822	862.663	195, 650.66	14.02	Main :: V 10...
Saturated Ste...			lb/hr	Mlb/yr			
	U-Steam	s9	6603.29	46.2242	2, 096, 717.75	150.22	Main :: V 10...
Electricity			KW	KWH/yr			
	Electricity	P 105	11.4265	99748.5	29, 924.56	2.14	Main :: P 105
	Electricity	P 211	2.30458	20136.6	6, 040.98	0.43	Main :: P 211
	Electricity	P 201	0.613328	5318	1, 595.40	0.11	Main :: P 201
Instrument Air			slpm	std m^3/yr			
	Instrument Air	FV 211	9.33931	4789.97	1, 436.99	0.10	Main :: FV 2...
	Instrument Air	LV 205	10.1652	5344.63	1, 603.39	0.11	Main :: LV 2...
	Instrument Air	FV 101	9.95712	5220.2	1, 566.06	0.11	Main :: FV 1...
Total					2, 334, 536.00	167.25	

Time : 0:30:57 (1857.2 s)

Fig. 22. Equipment status reporting

Fig. 23. Process utilities consumption

HFDS may help exam, verify and optimize various operating procedures. For example, HFDS produces not only the inlet and outlet temperatures and pressures of a heat exchanger, but also the fluid and wall temperatures, pressures and composition distribution inside the exchanger. The data can be used, for example, to analyze thermal stress during startup. For distillation column, temperature, pressure and composition distribution data are extensive and can be used to verify if a selected sensitive tray temperature is valid for composition control for certain operating conditions. Because of high-fidelity simulation, consumption of utilities such as electricity, instrument air, cooling water and steam can be dynamically calculated, so operation procedures and control designs can be evaluated based on energy cost and profit analysis.



1154.6

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☑ T-Tube1-5,F	■	227.75
☑ T-Tube1-6,F	■	227.322
☑ T-Tube1-7,F	■	226.899
☑ T-Tube1-8,F	■	226.483
☑ T-Tube1-9,F	■	226.072
☑ T-Tube1-10,F	■	225.667
☑ T-Tube2-1,F	■	221.904
☑ T-Tube2-2,F	■	222.258
☑ T-Tube2-3,F	■	222.616
☑ T-Tube2-4,F	■	222.979
☑ T-Tube2-5,F	■	223.348
☑ T-Tube2-6,F	■	223.721
☑ T-Tube2-7,F	■	224.1
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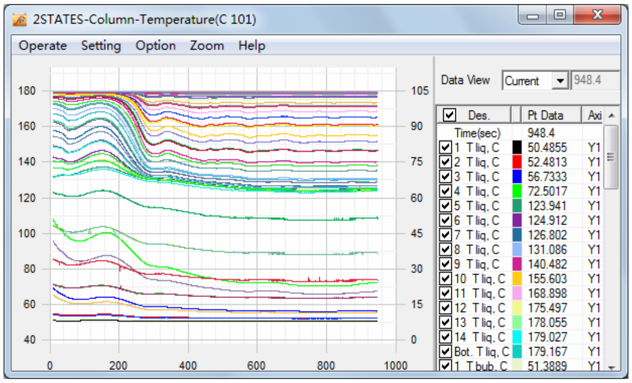

948.4

☑ Des.		Pt Data	Axi
Time(sec)		948.4	
☑ 1 T liq, C	■	50.4855	Y1
☑ 2 T liq, C	■	52.4813	Y1
☑ 3 T liq, C	■	56.7333	Y1
☑ 4 T liq, C	■	72.5017	Y1
☑ 5 T liq, C	■	123.941	Y1
☑ 6 T liq, C	■	124.912	Y1
☑ 7 T liq, C	■	126.802	Y1
☑ 8 T liq, C	■	131.086	Y1
☑ 9 T liq, C	■	140.482	Y1
☑ 10 T liq, C	■	155.603	Y1
☑ 11 T liq, C	■	168.898	Y1
☑ 12 T liq, C	■	175.497	Y1
☑ 13 T liq, C	■	178.055	Y1
☑ 14 T liq, C	■	179.027	Y1
☑ Bot. T liq, C	■	179.167	Y1
☑ 1 T bub, C	■	51.3889	Y1

Fig.24. Exchange temperature response during startup

Fig. 25. Column inside temperature responses

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