Beyond Single Loop PID Control: Model-Based and Combined Feedforward-Feedback Control

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OUTLINE

- Outline
  - Basic and Advanced Regulatory Control Definitions
  - Combined Feedforward-Feedback Control
  - Example 1: Combined Feedforward-Feedback Control of Distillation Column
  - Combined Feedforward-Feedback Tuning Methodology
  - Model-Based Control and Controller Types
  - Example 2: Cooling Tower Water Quality Composition Control
  - Summary

Basic Regulatory Control

- **Primary Process Control Objective**
  - **Controlled Variable (CV) stays within a predefined limit around the setpoint irrespective of routine disturbances that routinely affect the control loop**
- **Feedback Control**
  - **Single loop feedback control is adequate to meet the primary control objective for most processes**
  - **Effect of disturbances is not taken into account in advance**

Basic Regulatory Control (Cont'd)

- Basic Regulatory Control (BRC)
  - Basic instrumentation and control system hardware, software, and configuration required to safely operate the plant on a second-to-second basis
  - Should be able to handle routine load disturbances
  - Includes sequential regulatory control and batch logic if required
  - Includes required equipment interlock logic and safety, health & environmental controls

Advanced Regulatory Control

- Advanced Regulatory Control (ARC)
  - Extends control system capability beyond regulatory and sequential control to move the process closer to its economic optimum
  - Typically implemented to:
    - Improve operating efficiency and profitability
    - Increase plant production
    - Improve plant stability and operability
    - Better reject routine control loop disturbances

Advanced Regulatory Control (Cont'd)

- Advanced Regulatory Control (ARC)
  - Coordinates or ties together control for multiple loops
  - Typical Advanced Regulatory Control industrial applications:
    - Cascade control
    - Override control
    - Combined feedforward-feedback control
    - Model-based control (including Model Predictive Control)
    - Inferential composition control

Feedforward Control

- **Feedforward Control**
  - Sustained control error must have enough economic impact to justify higher design and implementation costs
  - Can minimize adverse effects of:
    - Large magnitude/frequent input disturbances
    - To some degree significant process lag
  - Effect of disturbance variable(s) on CV must be measurable
  - Cost/complexity trade-off

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Feedforward and Combined Feedforward-Feedback Control

- **Why Use Combined Feedforward-Feedback Control?**
  - **Feedforward control only is not practical because it requires:**
    - **Accurate modeling of the process**
    - **Ability to predict and model the effect of all possible disturbance variable(s) on the primary controlled variable (CV)**
  - **So Combined Feedforward-Feedback control is generally used**

Feedforward Control Types

- Steady-State Feedforward Control
  - Most simple and direct approach
  - No dynamic effects included
  - Instantaneous correction applied to manipulated variable
  - May not achieve control objective if dynamic effects are significant (and they usually are…)

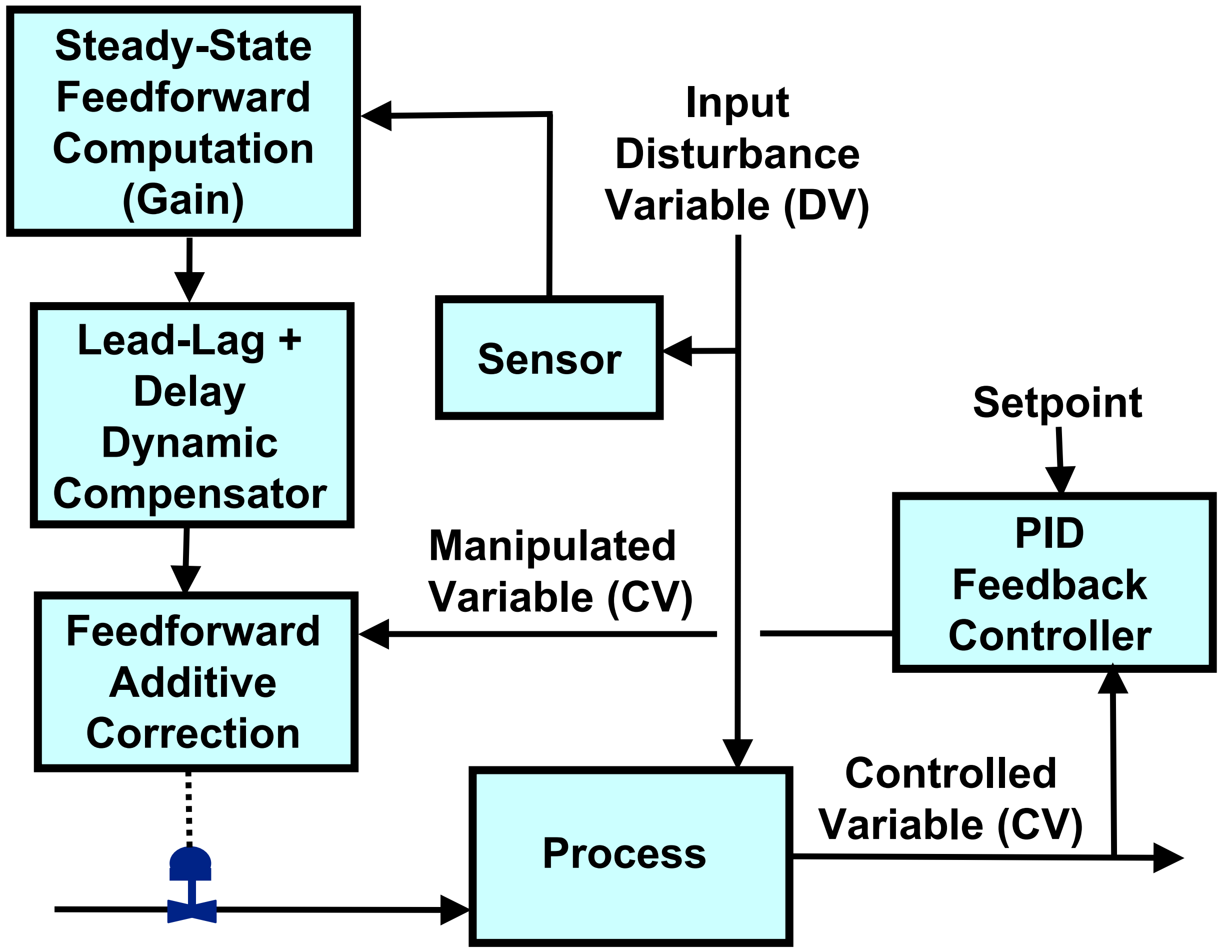
Feedforward Control Types (Cont'd)

- **Dynamic Feedforward Control**
  - **Takes into account:**
    - **Process dynamics (usually most significant)**
    - **Disturbance dynamics**
    - **Sensor dynamics**
  - **Can be implemented by:**
    - **Generic dynamic compensator (most common)**
    - **Application-specific feedforward control strategy and calculation**

Feedforward Dynamic Compensation

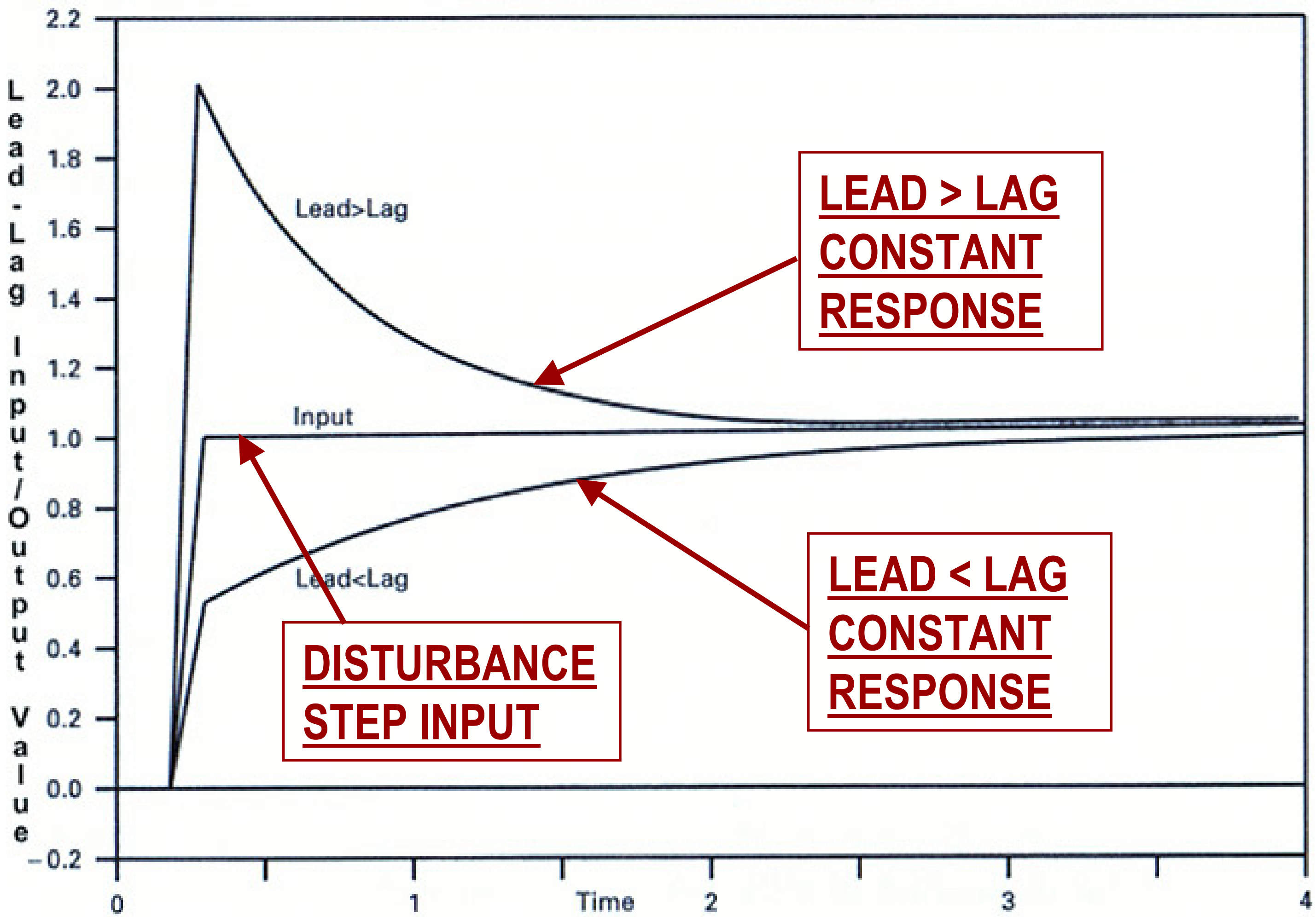
- ‘Generic’ FFD-FDBK Dyn. Compensator

DYNAMIC FEEDFORWARD CONTROL APPLIED AS AN ADDITIVE CORRECTION TO PID FEEDBACK CONTROLLER OUTPUT

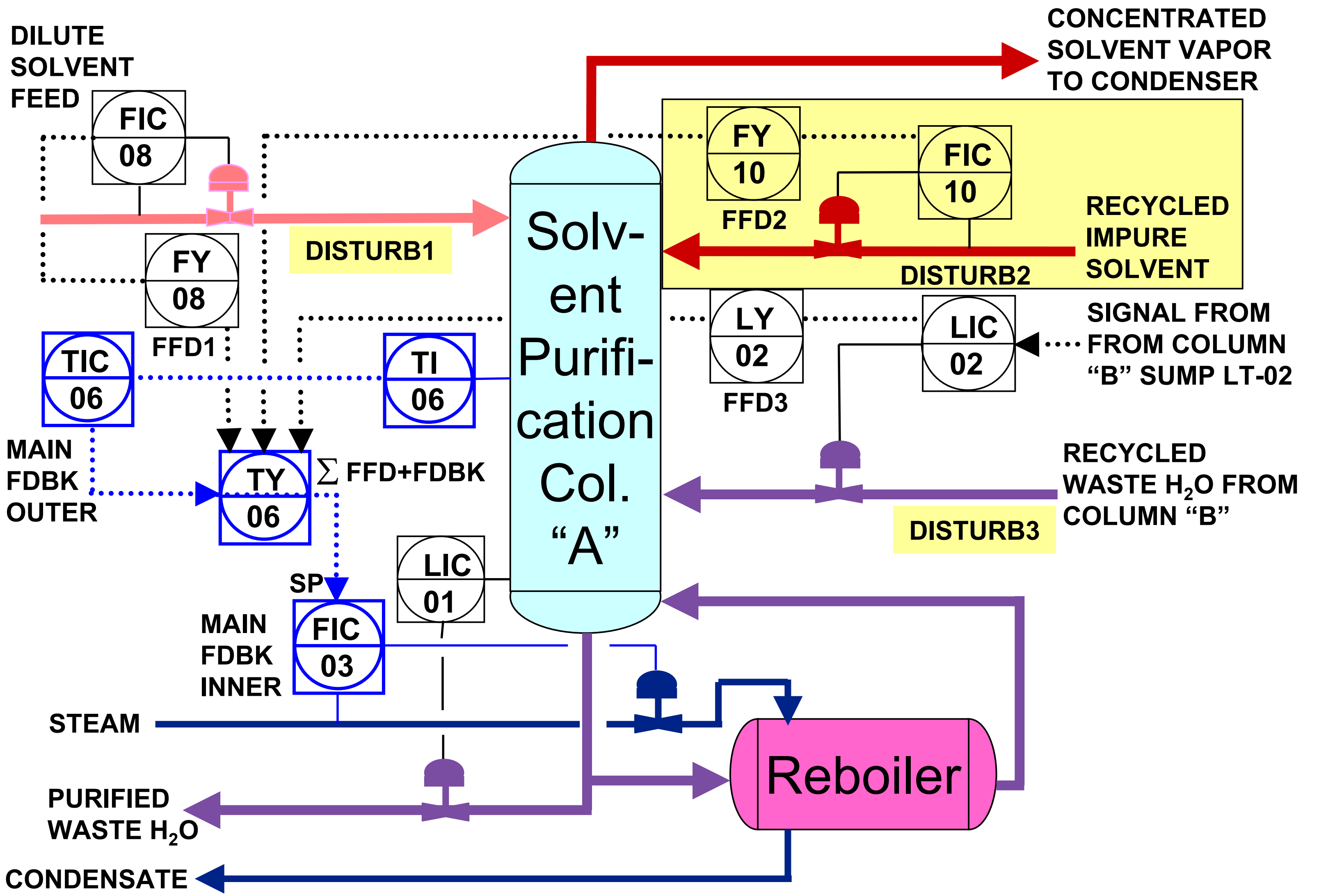


Feedforward Dynamic Compensation (Cont'd)

- **Feedforward Dynamic Compensation – Response of a Lead-Lag Dynamic Compensator to Step Input Change**



Example 1: Distillation Column Combined FFD-FDBK Control Process Schematic

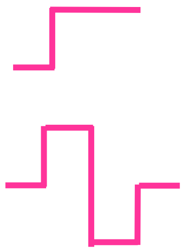


General Preparation for Tuning

- **BEFORE conducting any tuning exercises work closely with the operations personnel to:**
  - Establish the control loop performance criteria
  - Determine allowable operating and understand safety limits for the control loop and other affected variables
  - Obtain any necessary operations work and safety permits if required
- **Irrespective of tuning method used:**
  - Familiarize yourself with the process (there is no substitute for thorough process understanding!)
  - Understand in detail the data acquisition and control system and algorithms used including optional features

Feedforward Tuning Methodology

- Recommended Procedure
  - ALWAYS conduct at least 1-2 process response tests



    - Using an appropriate input disturbance such as a step or pulse (symmetrical or asymmetrical doublet pulse preferred)
    - Conduct process response tests at different parts of the normal operating range of the controlled variable
      - Average the results, assess nonlinearity
  - If cascades are present, conduct process response test(s) and tune inner feedback loop first
  - Conduct process response test(s) and tune the primary feedback controller

Feedforward Tuning Methodology (Cont'd)

- Recommended Procedure (Cont'd)
  - Continuously monitor and record the input disturbance variable (DV) and the primary feedback controlled variable (CV)
  - Put primary feedback controller influenced by input disturbance (feedforward) into Manual mode and allow the controlled variable to reach steady state
  - Manipulate the upstream variable that causes the input disturbance (e.g. vessel feed flow controller, level controller output, etc.) to create a series of input steps or pulses of varying magnitude and duration

Feedforward Tuning Methodology (Cont'd)

- Recommended Procedure (Cont'd)
  - Observe effect of disturbance on the primary CV and insure process response is in direction expected and magnitude of response is well above noise band
  - Put primary feedback controller influenced by input disturbance (feedforward) back into Auto mode
  - Allow primary controlled variable to reach steady state at same setpoint
  - If more than one input disturbance variable (DV) influences the primary feedback controller, repeat this procedure for each DV

Feedforward Tuning Methodology (Cont’d)

- **Recommended Procedure (Cont’d)**
  - **Perform process response test results analysis for each DV**
    - Using a tuning or model identification package [e.g., ExperTune, University of Connecticut’s (UConn) Control Station, MathWorks MATLAB + System ID Toolbox, etc.]
  - **Estimate input disturbance process gain (including sign), deadtime, and first order time constant**
  - **Use feedforward tuning constant rule set* or tuning and simulation package to obtain feedforward gain, lead, lag, and if req’d delay**
  - **Commission and test combined feedforward-feedback loop**

*The author’s rule set follows in next slide

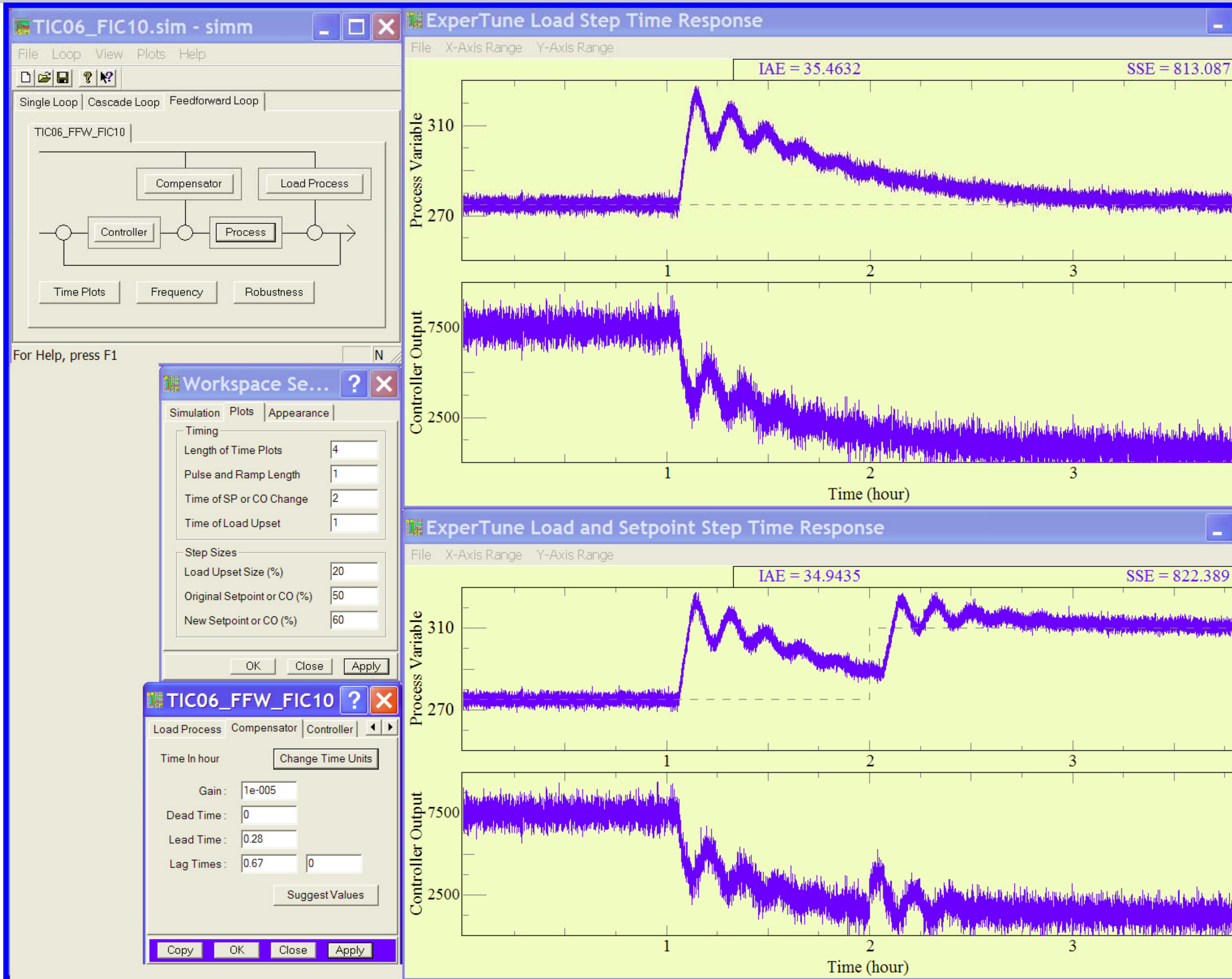
Feedforward Tuning Methodology (Cont'd)

- **Recommended Procedure (Cont'd)**
  - **1st pass feedforward tuning constant rule set**
    - Feedforward Gain = Load Disturbance Process Gain*/Controlled Variable Process Gain**
    - Feedforward Lead = (1.3-1.5) x Controlled Variable 1st Order Process Time Constant**
    - Feedforward Lag = (1.1-1.3) x Load Disturbance 1st Order Process Time Constant*
    - Feedforward Delay = Load Disturbance Process Deadtime* - Controlled Variable Process Deadtime** (ignore if less than 0)

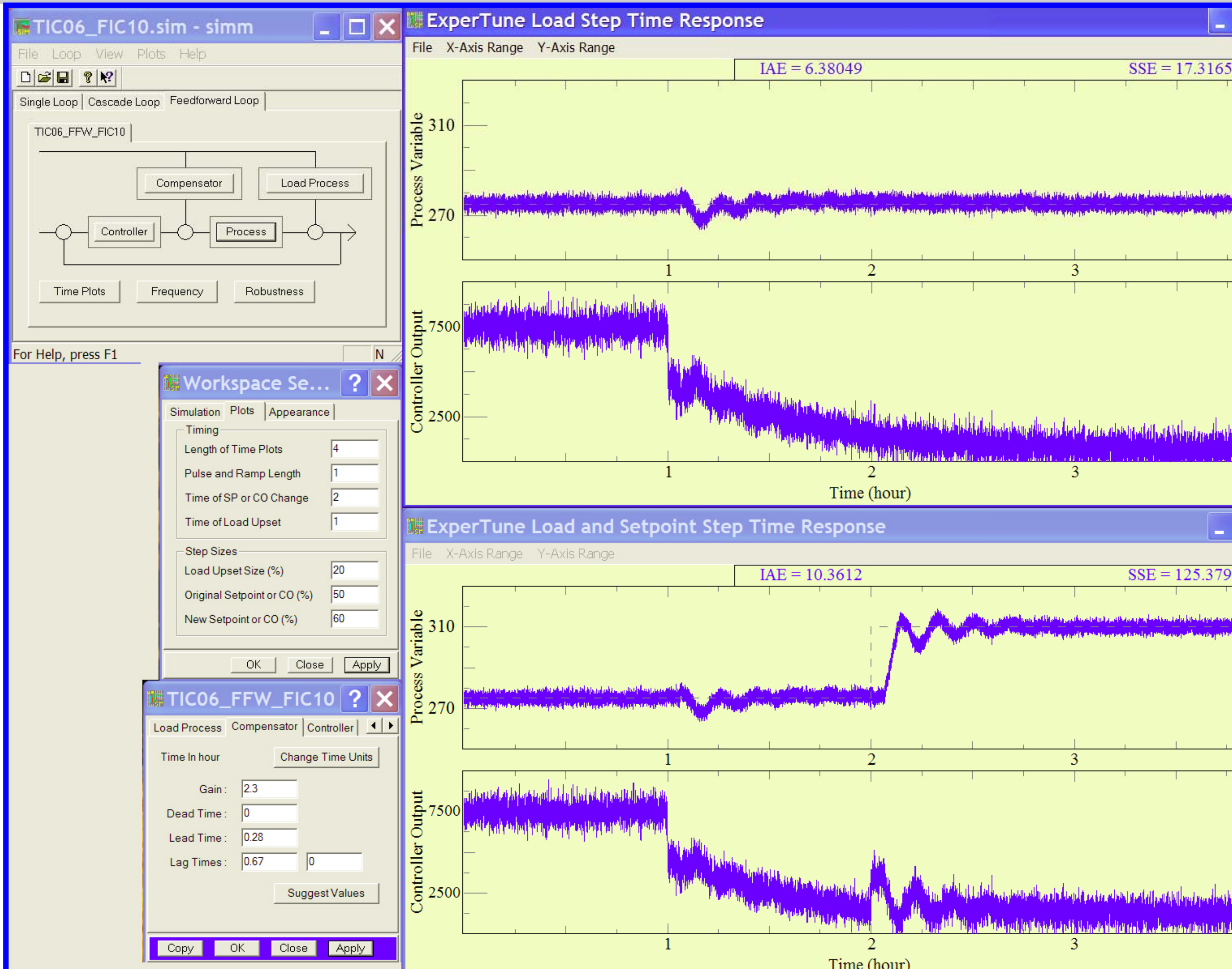
*Normalized effect of load disturbance variable (DV) change on primary process control var. (CV)

**Normalized effect of primary feedback controller manipulated variable (MV) move on primary process control var. (CV)

Simulated Feedback Only Temp. Ctl. Loop Performance – FIC10 20% Load Disturbance



Simulated Combined FFD-FDBK Temp. Ctl. Loop Performance – FIC10 20% Load Disturb.



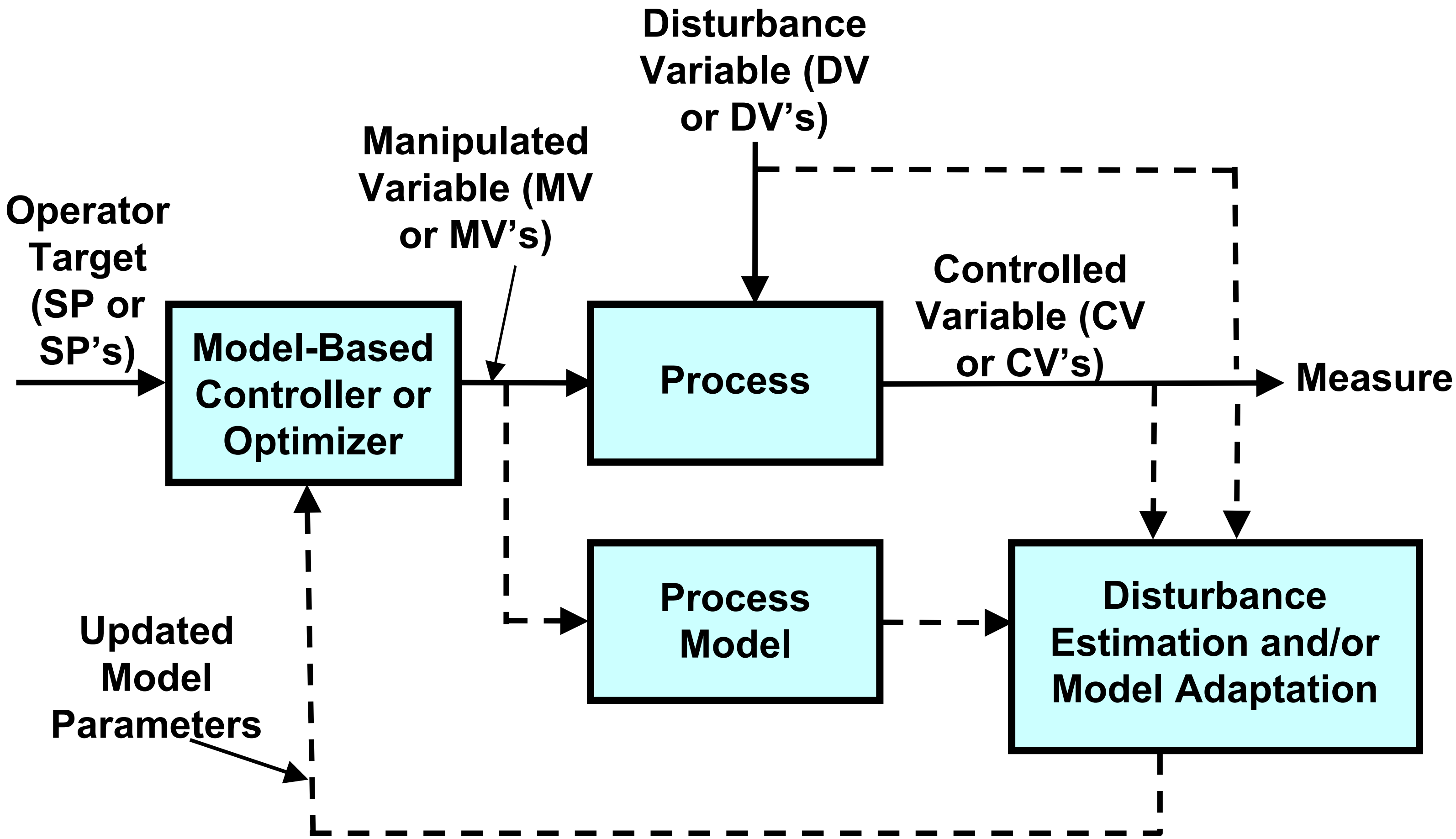
Example 1: Distillation Col. Combined Feedforward-Feedback Control Results

- **Adding three combined feedforward-feedback control loops with dynamic compensation achieved:**
  - **Routine solvent purification column operation within environmental emissions constraints**
  - **Substantially reduced solvent loss**
  - **Estimated savings:**
    - ~ $100K/year in solvent recovery
    - Unestimated $/year in avoidance of environmental emissions excursion fines

Model-Based Control

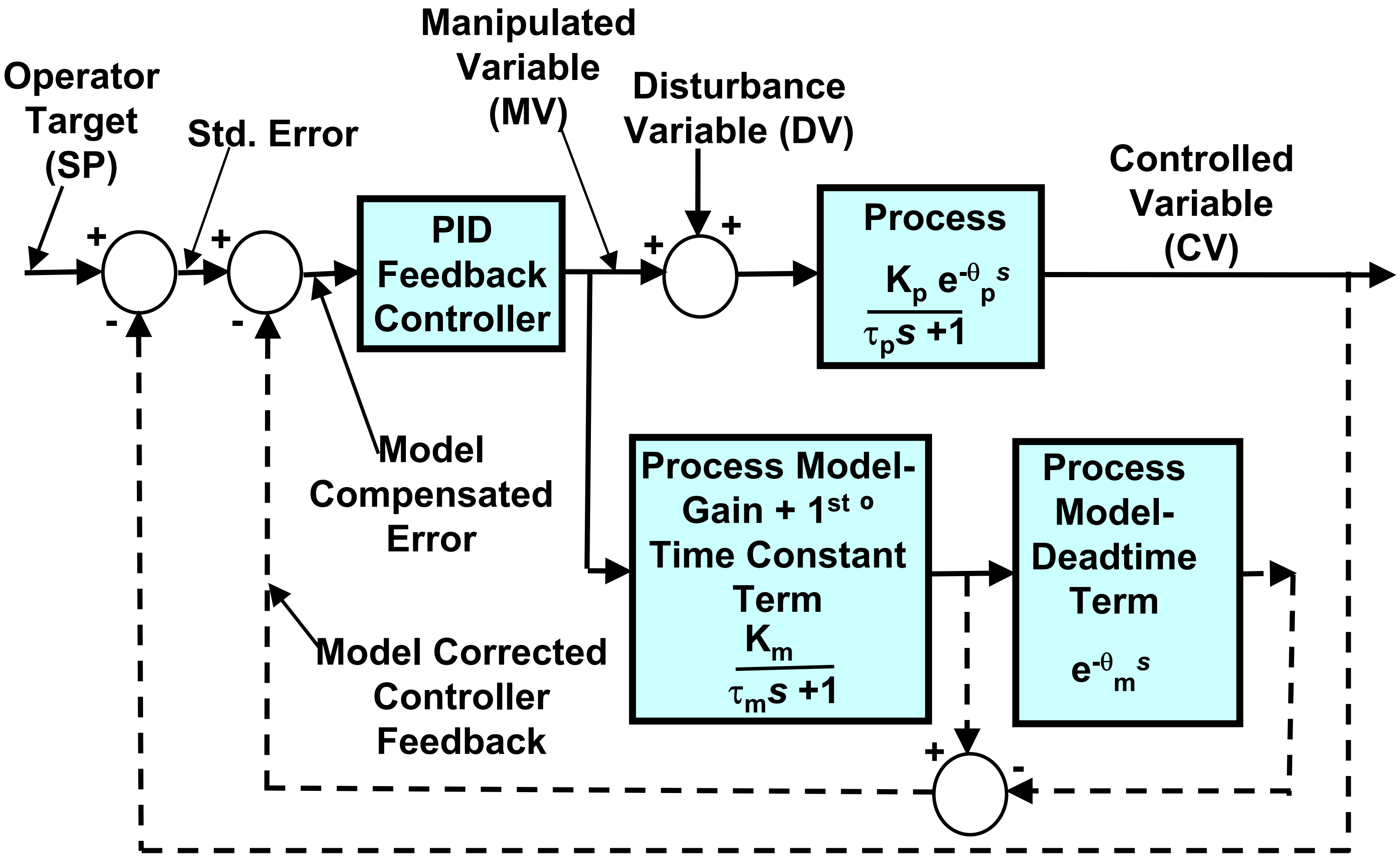
- What is Model-Based Control?
  - Embeds a process model in the control algorithm to better achieve the control objective
- Some Model-Based Control Examples
  - Internal Model Control
    - Smith Predictor with PID Feedback Control
  - Adaptive Model-Based Control – Feedback Controller Tuning Constants Online Adjustment
  - Adaptive Model-Based Control - Process Model Parameters Online Adjustment
  - Model Predictive Control
  - Many Other Variants and Commercial Products…

Generic Model-Based Control Block Diagram



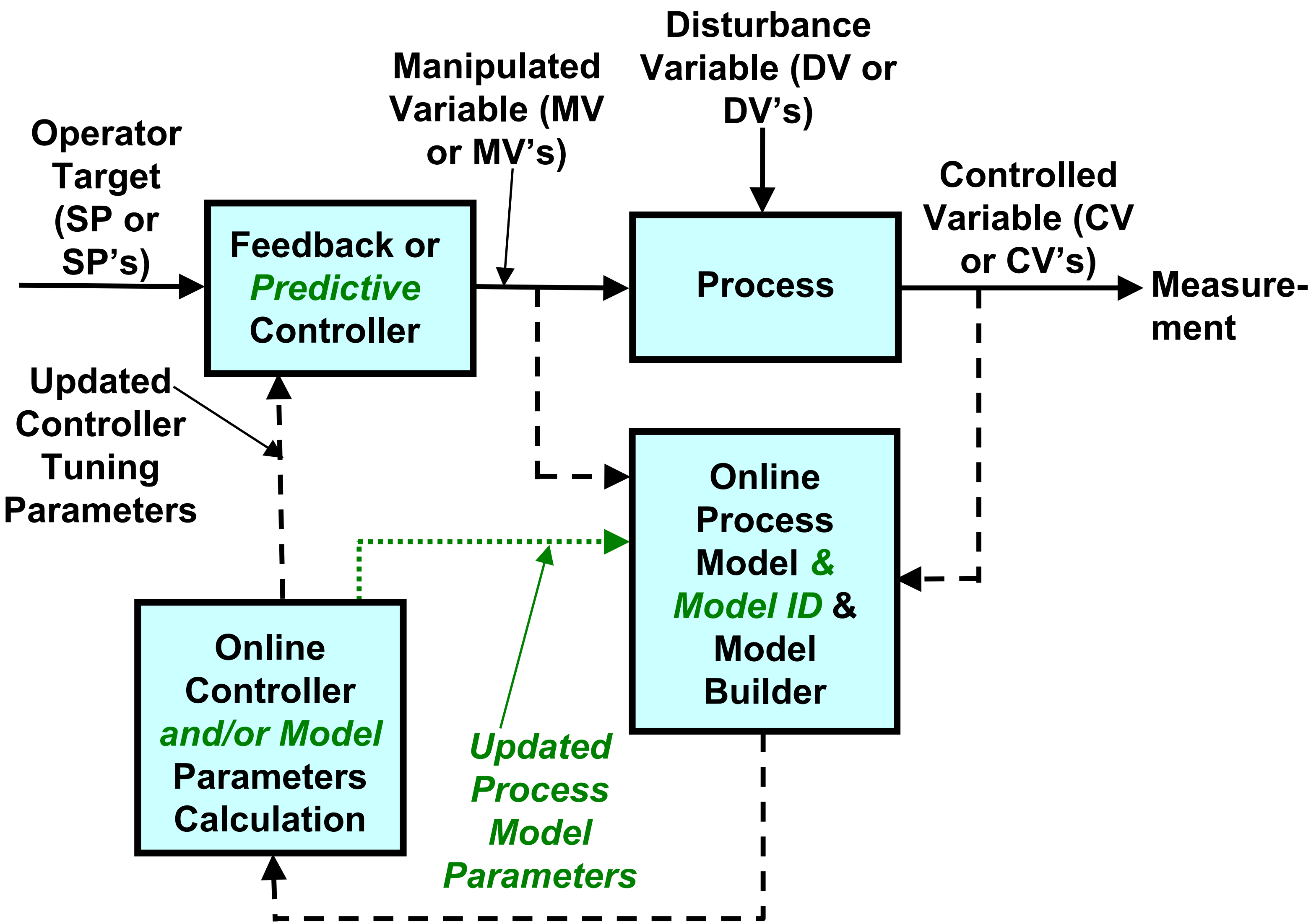
Note: the above diagram was extracted from <u>Techniques of Model-Based Control</u>, Brosilow & Joseph ©2002 Prentice-Hall, and was modified by the presenter.

Smith Predictor with PID Feedback Control Block Diagram



Note: the above diagram was extracted from Reg. & Adv. Reg. Control: Sys. Dev, H. L. Wade ©1994 ISA and Fundamentals of Process Control Theory 3rd e., P. W. Merrill ©2000 ISA, and was modified by the presenter.

Generic Adaptive Model-Based Control Block Diagram

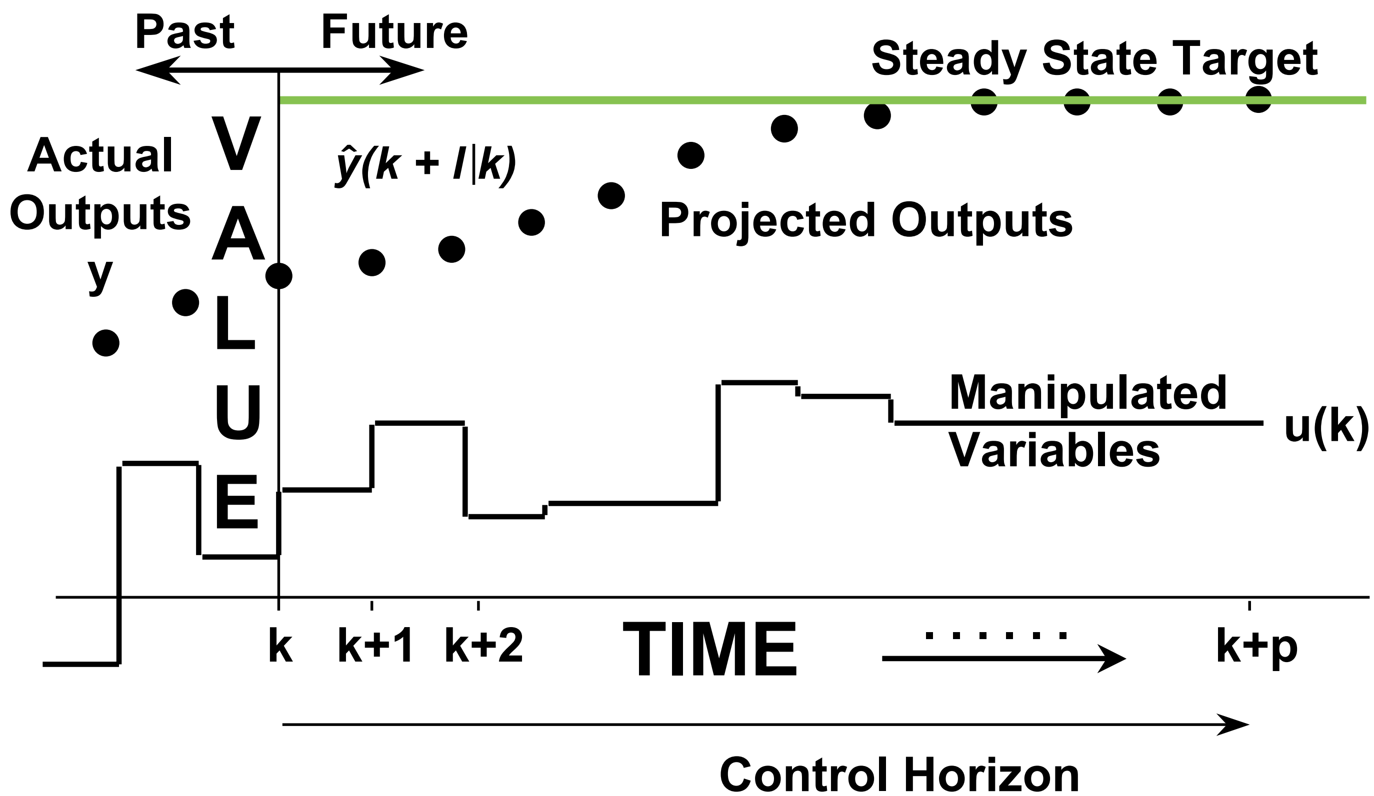


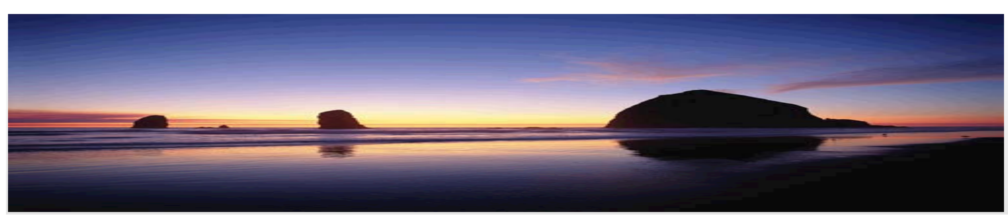
Note: descriptions in italics = capabilities of more sophisticated controllers

Model Predictive Control Definition and Features of Interest

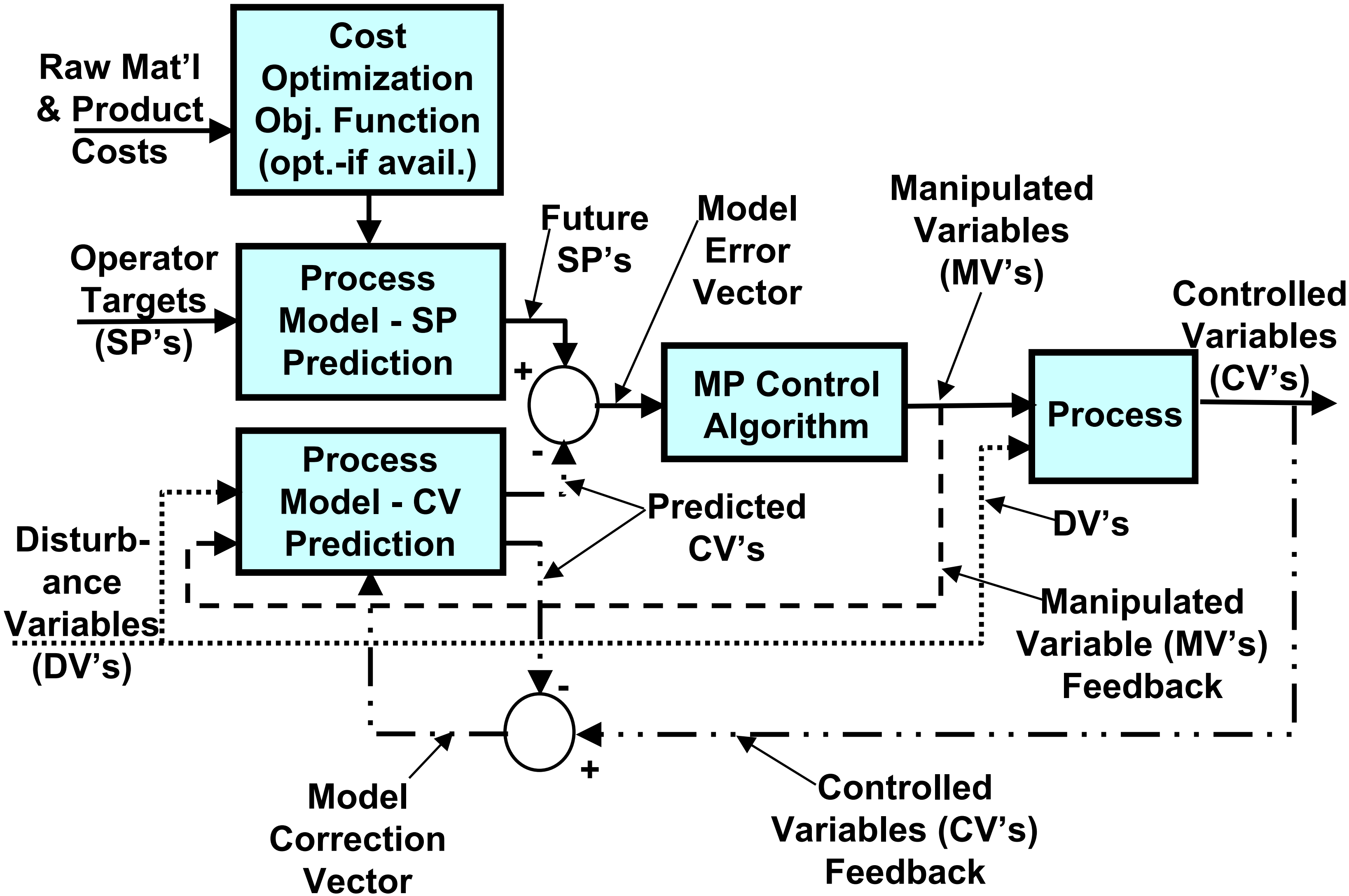
- **MPC- class of model-based control algorithms that compute a sequence of manipulated variable (MV) moves in order to optimize the future behavior of a plant**
  - **Solves control and optimization app mathematically online in real-time**
  - **Uses *linear* dynamic models to predict plant behavior (Feedforward)**
  - **Corrects for mismatch between actual plant behavior and model (Feedback)**
  - **May include operating constraints (constrained or unconstrained MPC)**
  - **May include dynamic cost optimization (objective) function**

How Model Predictive Control Works





Generic Unconstrained Model Predictive Control Block Diagram



Note: the above diagram was extracted from <u>Advanced Control Unleashed</u>, G. K. McMillan et al ©2003 ISA, and was modified by the presenter.

Model Predictive Control Advantages

- **Controls complex multivariable processes and can handle:**
  - **Large plant controller-related variable set**
    - Typical example: 100 CV’s/30 MV’s/10 DV’s
  - **Interactive variable and integrating process dynamics**
  - **Long dead time and time constant processes**
- **Can (depending on ctlr cap.) perform real-time economic optimization**
  - **Optimum SP range vs. single SP for each CV**
  - **Includes raw material and product costs**
- **Achieves fastest plant production rate ramping**

Model-Based & Adaptive Controller Suppliers

- Model-Based (Non-Adaptive) Controller Supplier
  - ControlSoft, Inc. MMC - Modular Multivariable Ctlr (2/3/0/0)
    - http://www.controlsoftinc.com/mmc.shtml
- Adaptive Model-Based Controller Supplier
  - Universal Dynamics Technologies BrainWave® (1/1/3/0) + BrainWave® MultiMax (12/12/36/NA)
    - http://www.brainwave.com/product/product_index.html
- Adaptive “Model-Free” Controller Supplier
  - CyboSoft™ (General Cybernation Group, Inc.) CyboCon (12/3/3/NA)
    - http://www.cybosoft.com/index.html

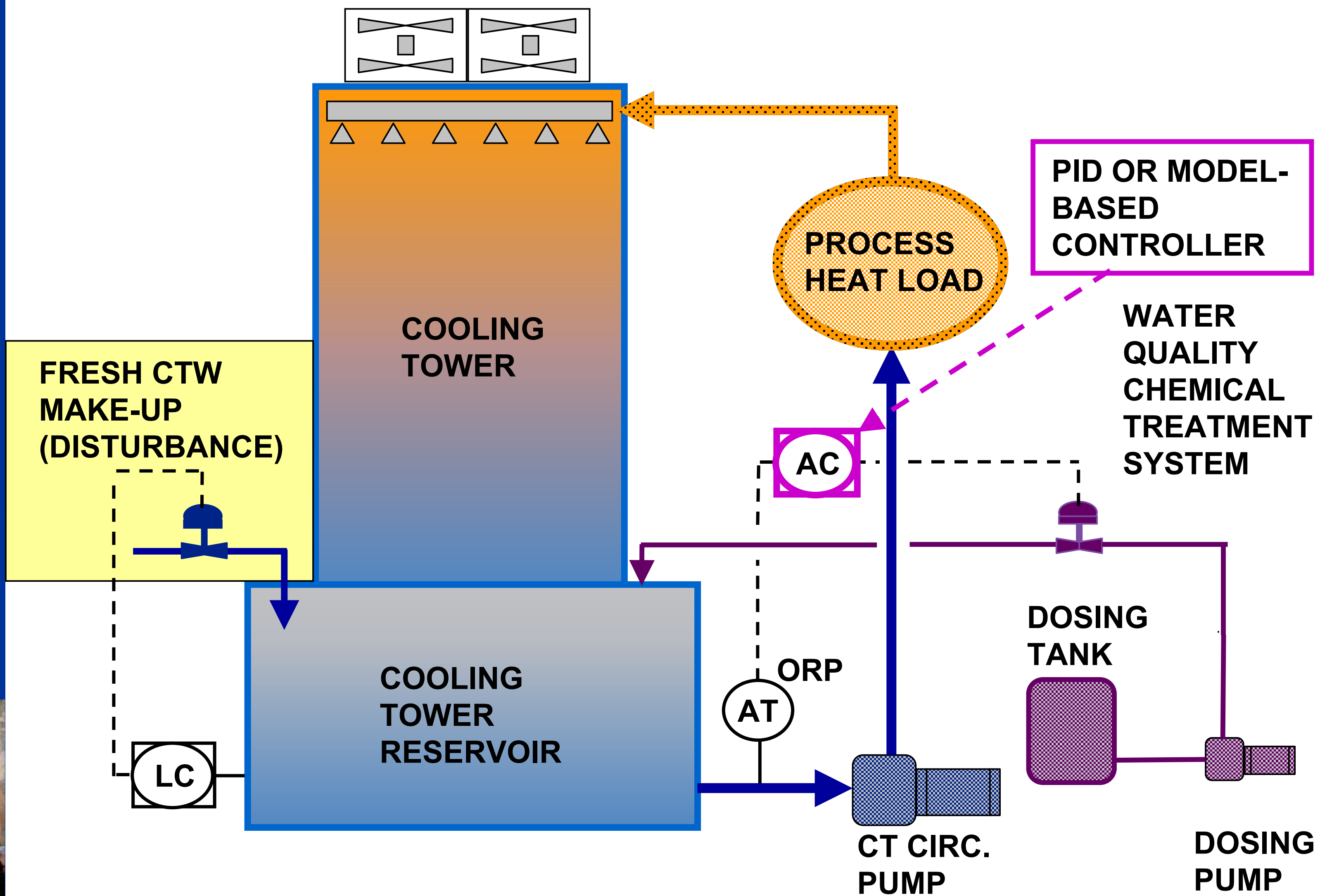
Note: (_/_/_/_) = controller capability for CV’s/MV’s/DV’s/AV’s (AV=constraint)

Model Predictive Controller Suppliers

- **Model Predictive Controller Suppliers**
  - **Aspen Technology DMCplus® (100's/100's/etc.)**
    - http://www.aspentech.com/
  - **Emerson Proc. Auto. DeltaV™ Predict (4/4/4/4)**
    - http://www.easydeltav.com/
  - **Honeywell Profit® Robust Multivariable Predictive Controller (200/100/100/300)**
    - http://www.acs.honeywell.com/ichome/
  - **Intelligent Optimization GMAXC™ (40/25/10/40)**
    - http://www.intellopt.com/GMAXC.htm
    - 3rd party S/W solution from Siemens Energy and Automation Div. for APACS+ systems (http://www.sea.siemens.com/process/default.html)

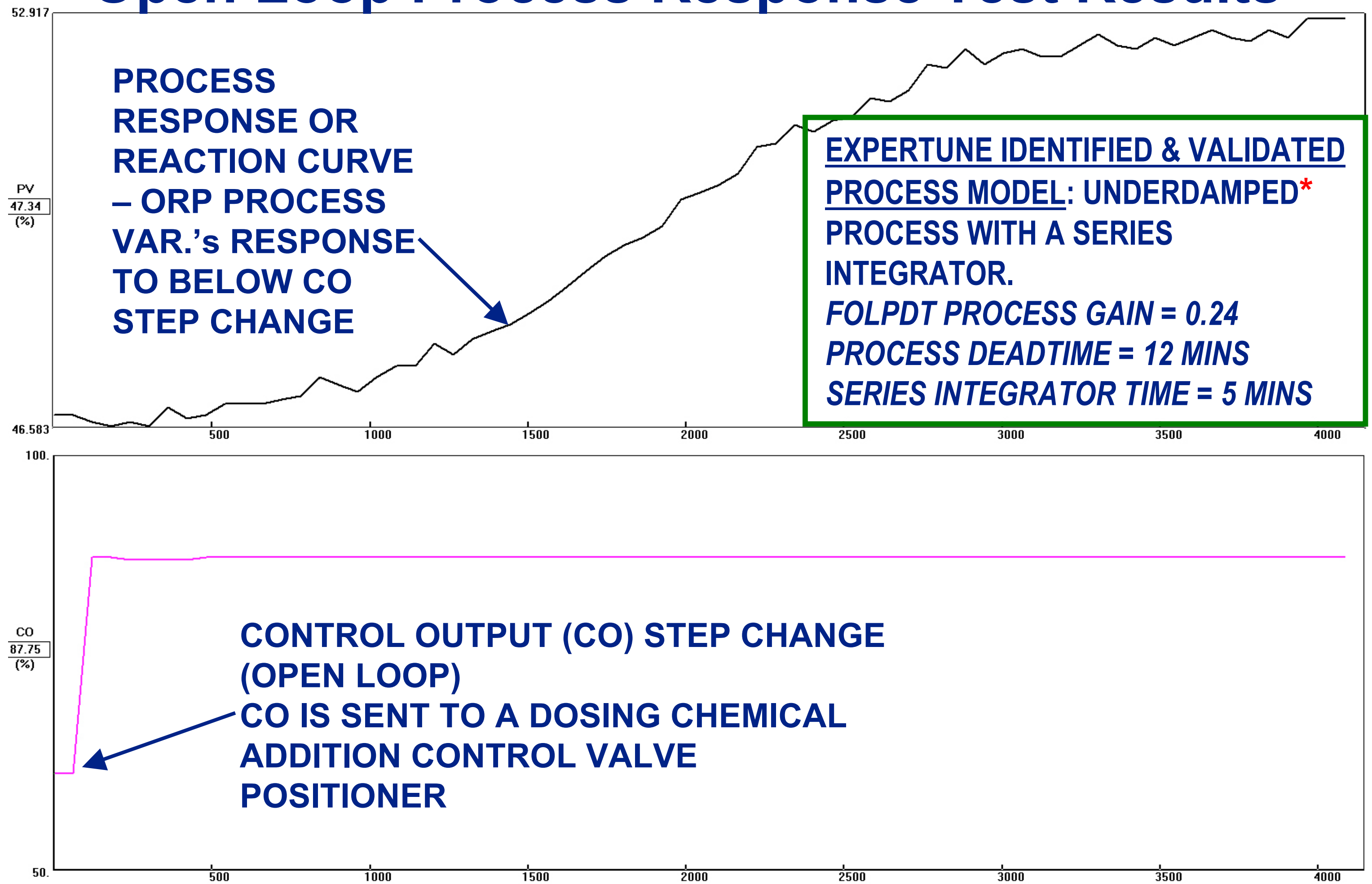
Note: (_/_/_/_) = controller capability for CV's/MV's/DV's/AV's (AV=constraint)

Example 2: Cooling Tower Water Quality Composition Control Process Schematic



Example 2: Cooling Tower Water Quality Composition Control – Process Identification

Open Loop Process Response Test Results



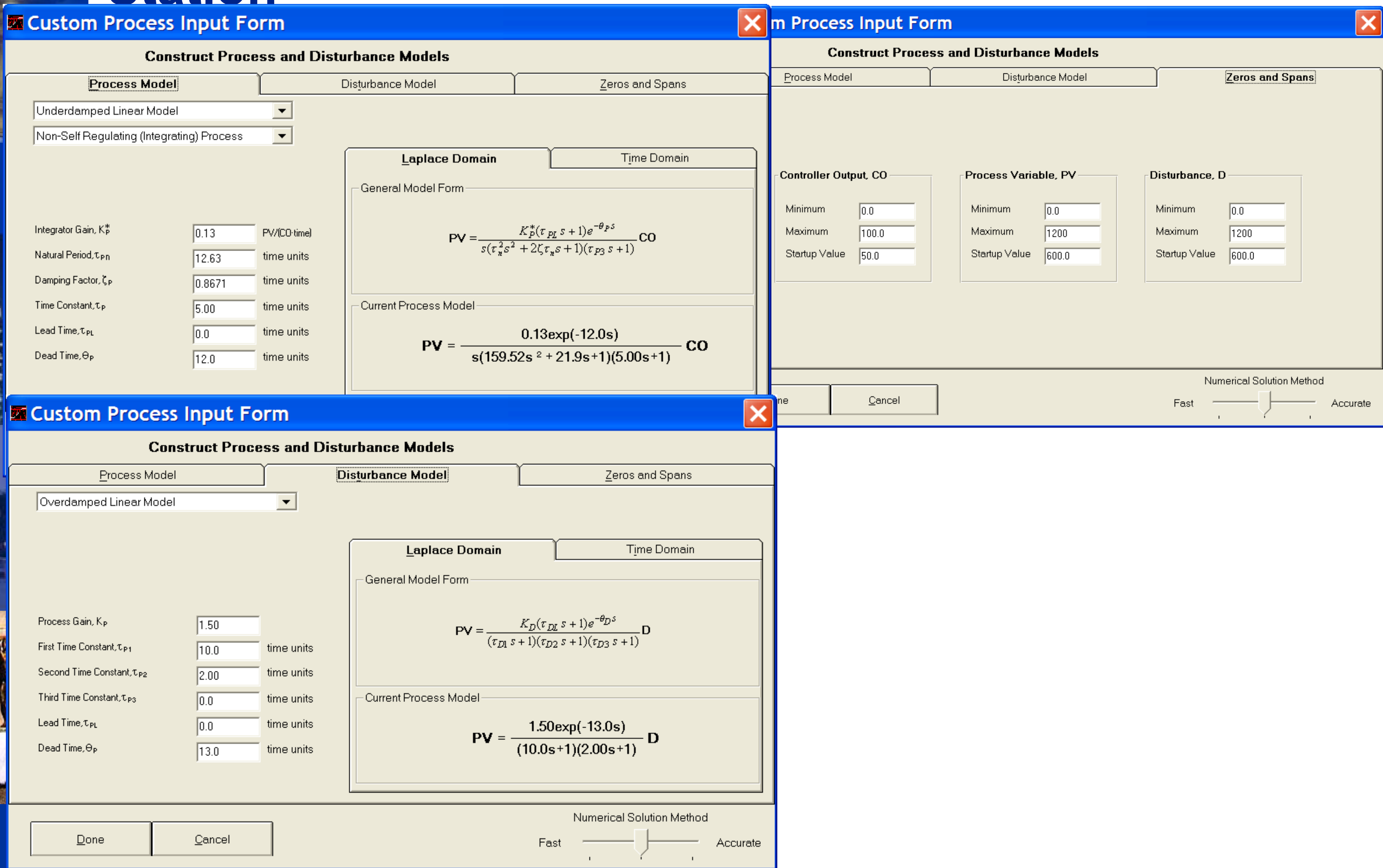
⇑ ENGR UNITS (% of PV or CO range)

⇒TIME UNITS (secs)

*The Laplace polynomial equation used to model and simulate this underdamped process in the ExperTune Loop Simulator is: $1/(C0 + C1s + C2s^2 + C3s^3)$: C0=4.2; C1=92; C2=670; C3=0.

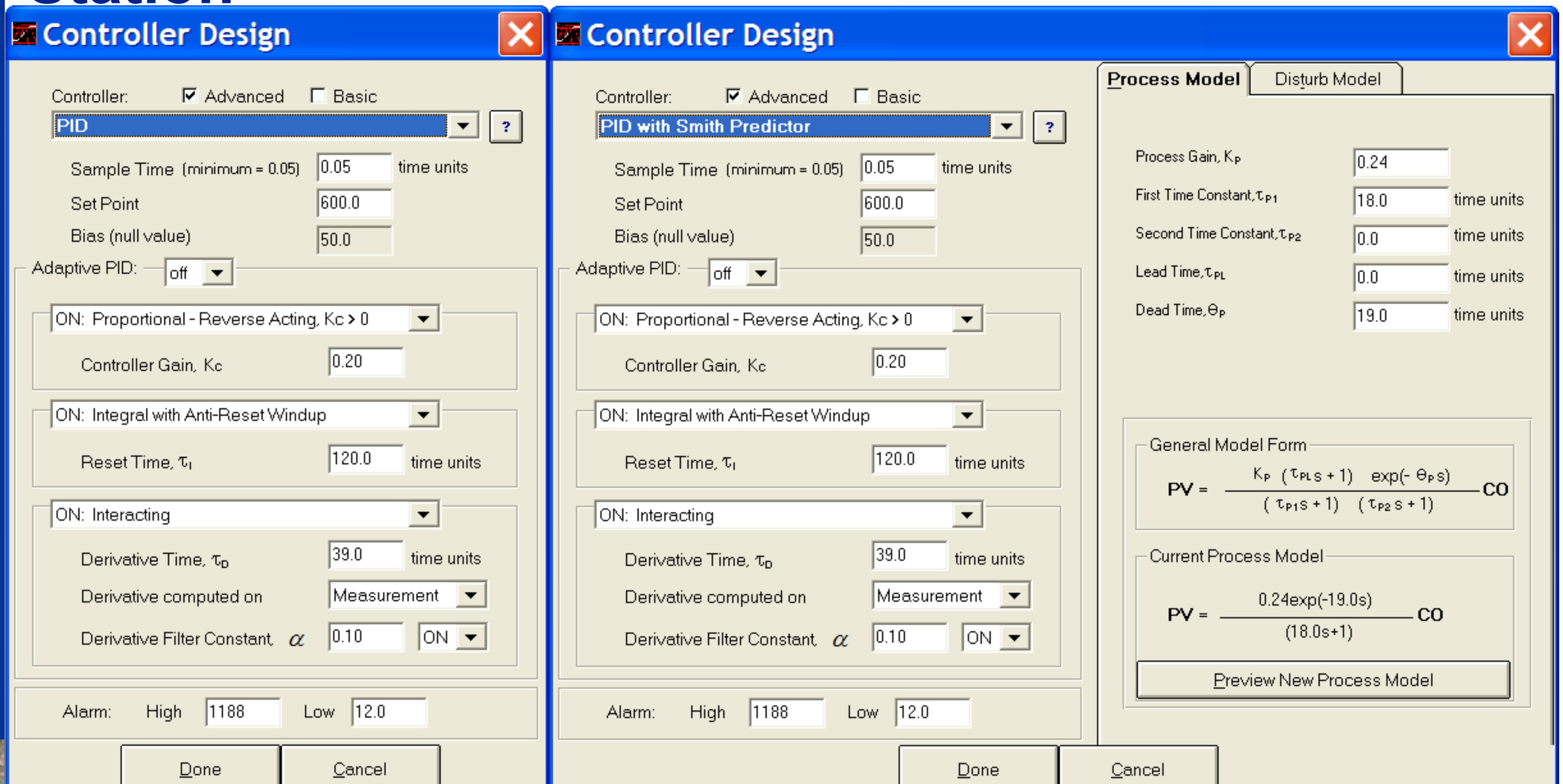
Example 2: Cooling Tower Water Quality Composition Control – Process Model Dev.

Simulated Process & Disturbance Models – Control Station

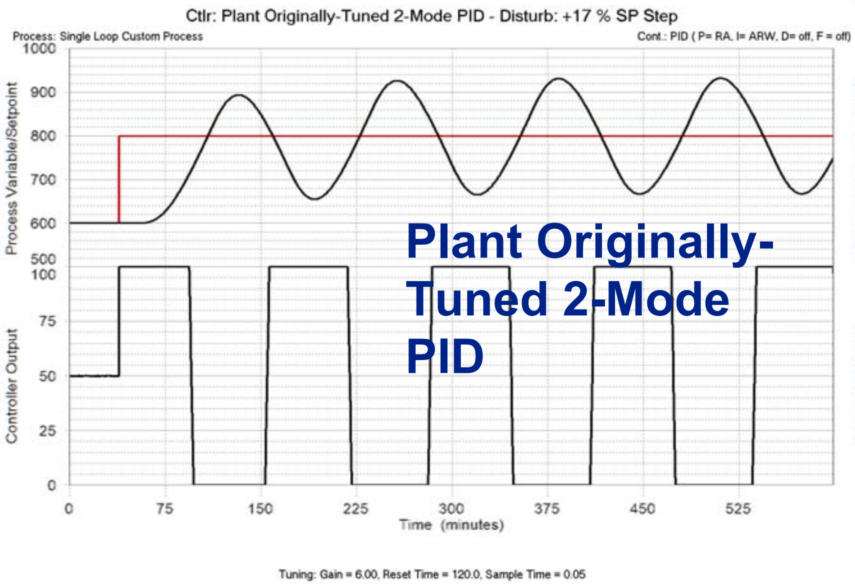


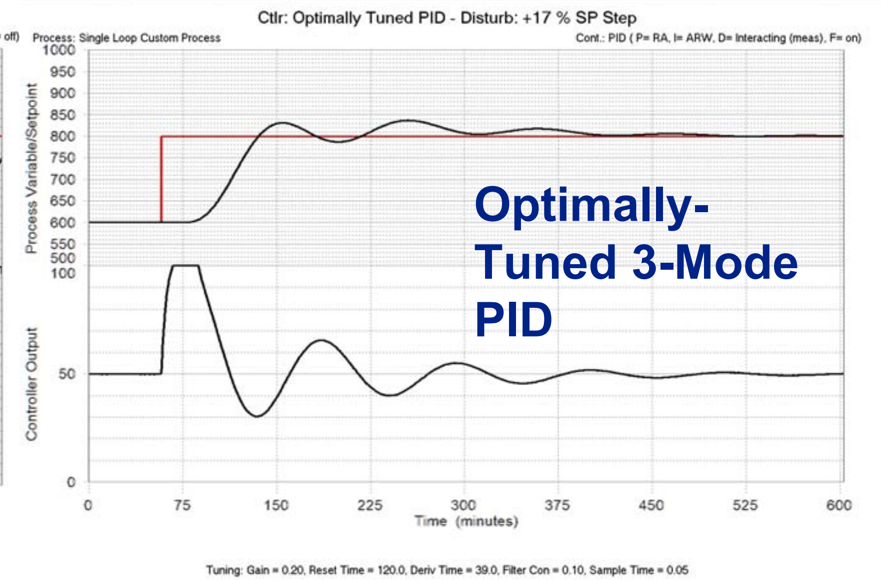
Example 2: Cooling Tower Water Quality Composition Control – Controller Dev.

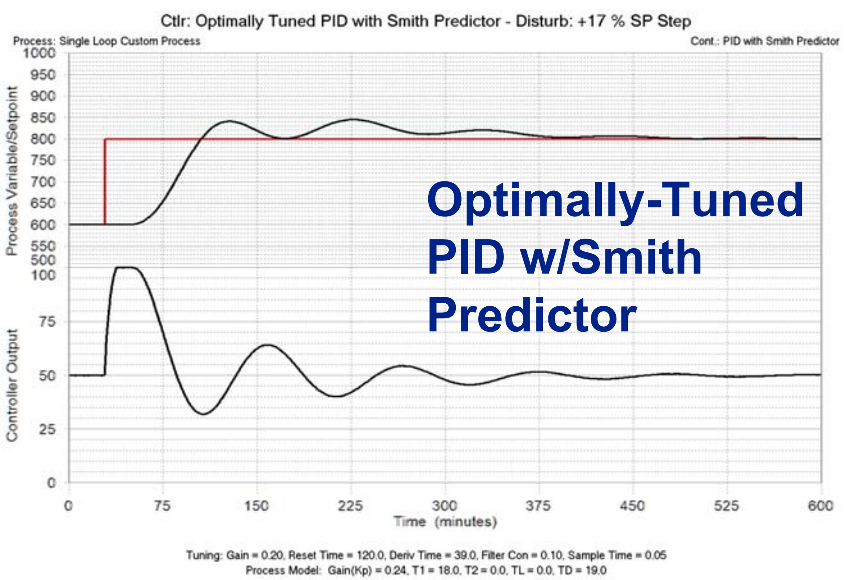
Simulated PID & Model-Based Controller – Control Station



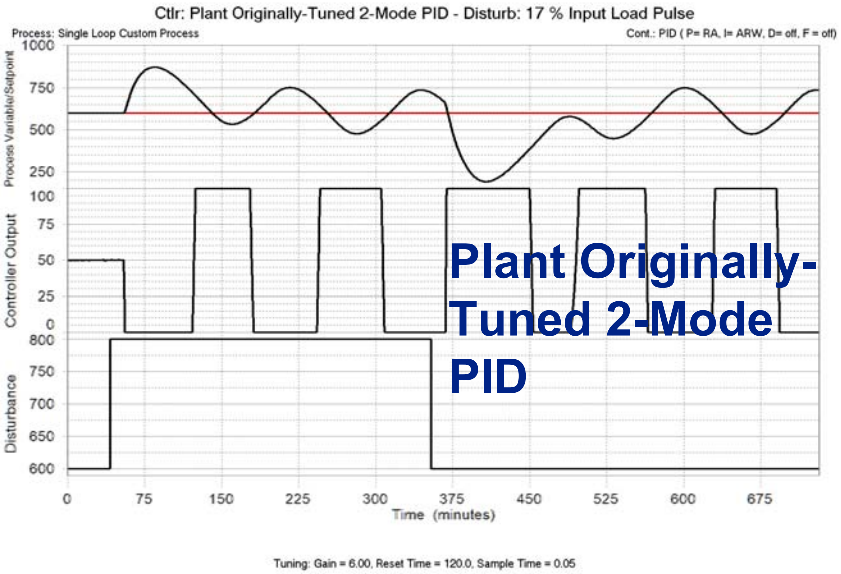
Example 2: Cooling Tower Water Quality Comp. Ctl Simulated Perform. – SP Step

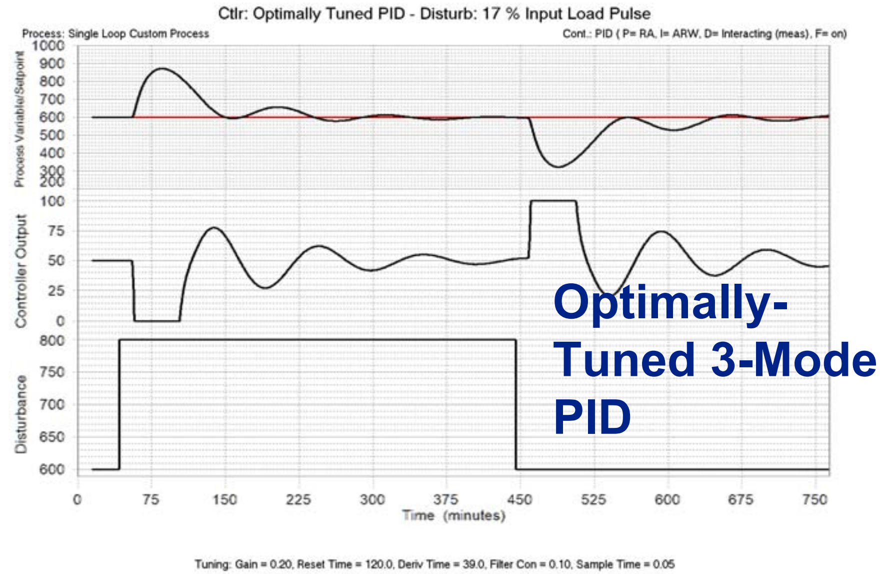


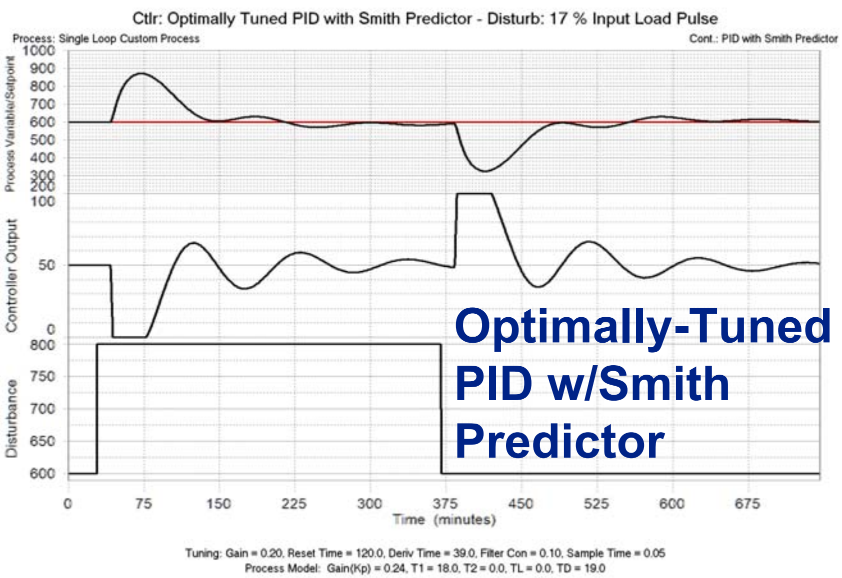




Example 2: Cooling Tower Water Quality Comp. Ctl Simulated Perform. – Load Pulse







Example 2: Cooling Tower Water Quality Composition Control Results

- **Optimal PID Control Tuning Results:**
  - **Retuned with step and pulse response testing using ExperTune**
  - **Retuned loop reduced average ORP Controlled Var. (CV) variance from +/- 20-45% before retuning to ~ average of +/- 5% after retuning**
  - **Estimated savings:**
    - Avoidance of need to shut down the plant and manually chemically clean heat exchange equipment ~ once/year - $100K
    - $5K per year in reduced microbiocide usage

Summary

- **Advanced Regulatory Control - globally proven to provide major competitive advantage if properly applied and maintained**
  - **Combined Feedforward-Feedback control can minimize the negative impact of routine disturbances for high profit control loops**
  - **Model-Based and Model Predictive Control can handle difficult or complex applications where single loop feedback control is not adequate**
  - **These techniques have been successfully applied to greatly improve plant performance for many decades**
- **Very capable commercial tools are now available to facilitate the process of moving *beyond single loop control***