# Past, Present and Future Trends in the Implementation of PID Control Algorithms

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When a system changes from pneumatic control to Direct Digital Control (DDC), installers and site engineers lose the analog gages and logic they previously used to monitor the system. They also find it more difficult to tune DDC control algorithms properly and tend to set operating variables at less-than-optimum values, thus negating the benefits of controller technology. To maximize utilization of advanced controller equipment, field engineers must have proper initial values for the gains in Proportional-Integral-Derivative (PID) calculations, and they must have adequate tools to monitor the effects of PID operation and adjust gains as needed. This paper discusses simulation of common Heating, Ventilating, and Air Conditioning (HVAC) applications to arrive at initial recommended gains and graphical on-site tools that can help personnel adjust those values for optimal system performance. Additionally, the implementation of adaptive control through the use of neural nets to enhance the performance of the PID loops is discussed to minimize (or eliminate) the requirement for manual tuning and to provide robust control.

## PROBLEMS AT CHANGEOVER TO DDC

When a system changes from pneumatic to direct digital control, several problems normally arise:

- The digital panel no longer provides detailed, on-line information about control logic as the pneumatic panel did.
- DDC software algorithms hide the detailed information. If any flowchart and/or control logic information is available, it shows only the initial setting but not any on-line information.
- The application engineer or technician on site needs to tune the proportional-integral-derivative loops, which is a tedious, time-consuming process.
- There are no on-line tools to show detailed operation and the result of PID value change on operation of the mechanical systems and other loops.

If site personnel start with values that are reasonable estimates for the type of HVAC application, they can reduce tuning time. An on-line, graphical, computer-aided tool can help make final tuning easier and more informative.

## RECOMMENDED PID GAINS

The PID control equation is expressed as follows:

$$U = Uo + Kp * e + Ki \int e * dt + Kd * de/dt$$

Where:
U—the controller output (%)
Uo—the output bias (%)
Kp—the proportional gain (%/oF)
e—the error (oF)
Ki—the integral gain [%/(oF * sec)]
Kd—the derivative gain (% * sec/oF)

The proportional control is used to provide the maximum gain across a process when the actuator travels from closed to fully open conditions. Thus, the process output is at set point only at mid-point. At all other load conditions the there will be an offset, i.e. the output from the process does not equal the set point. The integral control is used when the sensor that measures the output from the is located next to the process. The derivative control is important for applications where there is a considerable delay from the process to the sensor. In general, the gains are not known apriori and tuning is required. Tuning, in the building industry has been done on-site by experienced people. In the era of pneumatic control (proportional control only) it was not as difficult to tune the control loops, but with the emergence of software based controllers the complexity increased considerably. Because the tuning of PID-based DDC controllers is tedious and time-consuming, many installers (due to lack of proper information) compromise performance to minimize on-site tuning time. This action negates the benefits of sophisticated DDC control with respect to analog control.

Controller suppliers and installers do not always have the experience (knowledge base) to tune the system. Also, due to attrition, new people need to learn and understand the dynamic operation of the HVAC system in order to do the tuning. As mechanical system design engineers provide new system design alternatives and new equipment, the difficulty of tuning increases. There is a need to capture the information (knowledge base) to make it available to all other installers. There is also a need to enhance the knowledge base for new applications as well as for various constraints that may appear under various conditions. For this purpose, simulation of various applications and their control logic helps to define initial gains for a PID-based DDC controller. These PID gains (based on experience and analysis) are stored in commissioning tools. Thus, whenever the field application engineer configures a control system, the recommended PID gains automatically load into the controller.

The following sections examine:

- Definition of PID gains by analysis (simulation).
- How the field application engineer selects the recommended gains and how the commissioning technician can monitor the operation of the system and vary the gains if necessary.
- Adaptation/compensation of the PID loop with Neural Networks

## SIMULATION OF HVAC PROCESSES AND THE ASSOCIATED CONTROL

Simulation tools can help define the recommended PID gains. Mixed air control is a typical application. The benefit of simulation is that a control engineer at the home office can analyze many different of configuration of static and dynamic control loop characteristics to recommend PID gains such that in many cases the controllers will work satisfactorily and only fine tuning will be required.

### Mixed Air Control

One of the more common loops in HVAC systems is mixed air control. In this type of loop, return air from the building and outdoor air are mixed to supply air at some desired temperature. The control loop consists of three components: a sensor to detect the mixed air temperature, an actuator/ damper to regulate the amount of outdoor air brought in, and a controller to modulate the actuator/damper position based on the sensor input. Since outdoor air temperature can fall below 32F, there must be some provision for freeze protection in order not to damage the cooling coil.

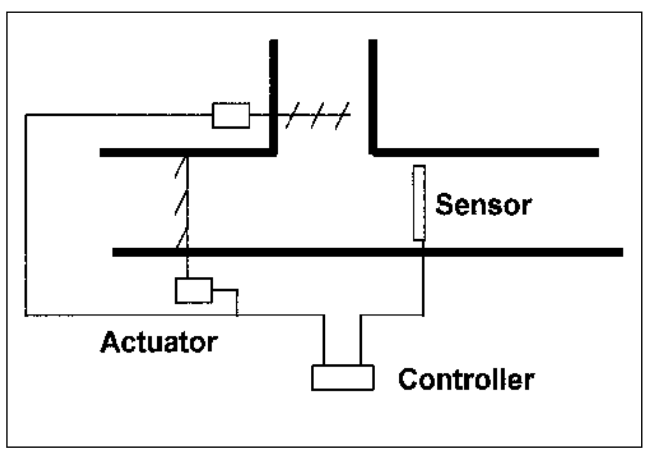
Figure 1 shows the model of a mixed air control loop. While there is more than one configuration of a mixed air loop, the selected model is the most typical. The time-dependent behavior of the control loop is very important in this case since the process (mixing of the return air with the outdoor air) is very short. In simulation of the dynamic behavior of the loop it is necessary to specify the time constant of all the devices that compose the specific system. The following time constants were used in simulating the performance of this system:

- Sensor, 35 seconds
- Actuator, 10 seconds
- Mixing process, 2 seconds

The actuator model had 10% hysteresis and was fed by a capacity feed device which resulted in the fast response of the actuator. This model simulated the response of a mixed air loop to PID control. To create a disturbance in the loop, initially the damper was full open and the mixed air temperature was that of the outdoor air. The controller set point was then shifted to 55F to simulate a step input.

Figure 2 shows the recommended proportional gain (KP) for a given set of integral gain ($K_I$**)** and derivative gain (**$K_D$**) as a function of sample interval. The figure summarizes the result of simulation of proportional control for sample intervals of 0 to 20 seconds. The results for this mode of control display in two curves: the *Recommended* curve represents the best performance while maintaining minimum offset, and the *Acceptable Upper Limit* curve values that can be used when smaller offset is desired but when longer settling time (time to get is acceptable. The determination of a recommended KP was based on the results of simulations of model response to a step input at a given sample interval with different KP. The Recommended KP chosen

***Figbure 1.***



gave the shortest settling with minimum droop. Proportional gain, KP, can be thought of as a change of controller output per unit error.

At each sample interval, the recommended KP for proportional control was used and the integral gain was varied to give the smallest settling time. Addition of the derivative mode of control allows an increase in the integral gain due to the increase in stability.

Using a five-second sample interval as ''typical'' of DDC controllers, Figure 3 shows system response to the recommended values of KP, KI, and KD when set point is 55F. Note how the mixed air temperature flattens at the peaks and valleys due to actuator hysteresis. Graph (3.a) illustrates the results for proportional control; the system comes to equilibrium quickly but droop is present. PI control, Graph (3.b), eliminates this droop. With the addition of the derivative mode of control, Graph (3.c), settling time also decreases.

Figure 4 illustrates the system sensitivity to changes in KP and KI. Graph (4.a) shows system performance with the recommended PI gains. In Graph (4.b), KP is doubled, and in Graph (4.c), KI is doubled. Note that an increase in integral gain independently of proportional gain causes an increase in oscillations, and settling time is longer. Increasing the recommended KP causes oscillation with a shorter time period and a larger amplitude; settling time also increases.

Figure 5 shows system response to PID control with varying KI and KD. Graph (5.a) in illustrates system response with the recommended gains. In Graph (5.b), integral gain is doubled. There is some undershoot, but the system comes to equilibrium at set point quickly. Doubling the derivative gain, Graph (5.c), does not make any significant change to system performance.

***Figure 2.***

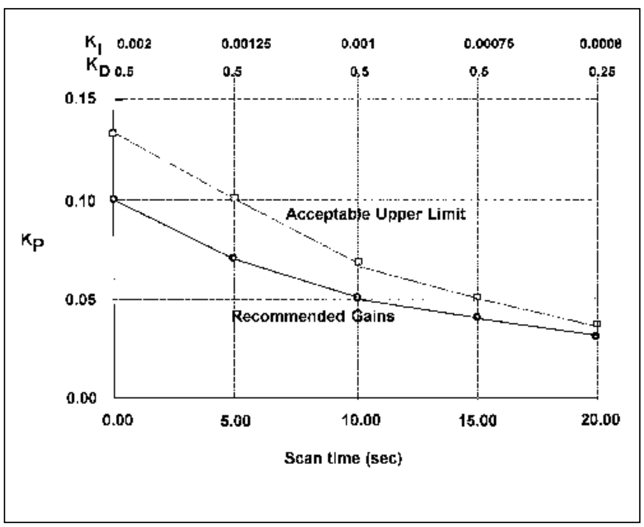



***Figure 3.***

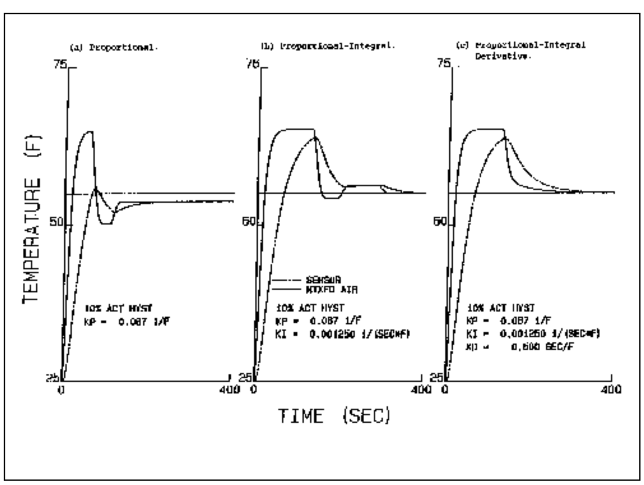



***Figure 4.***

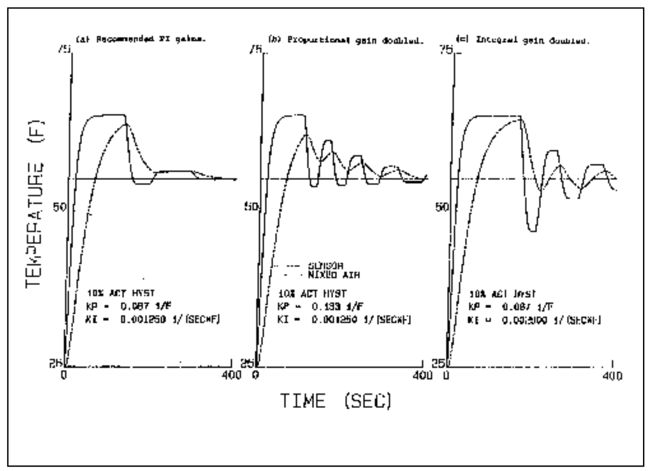



***Figure 5.***

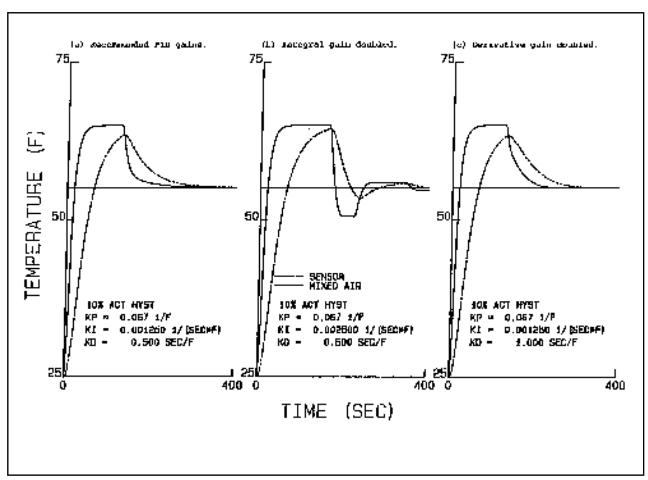
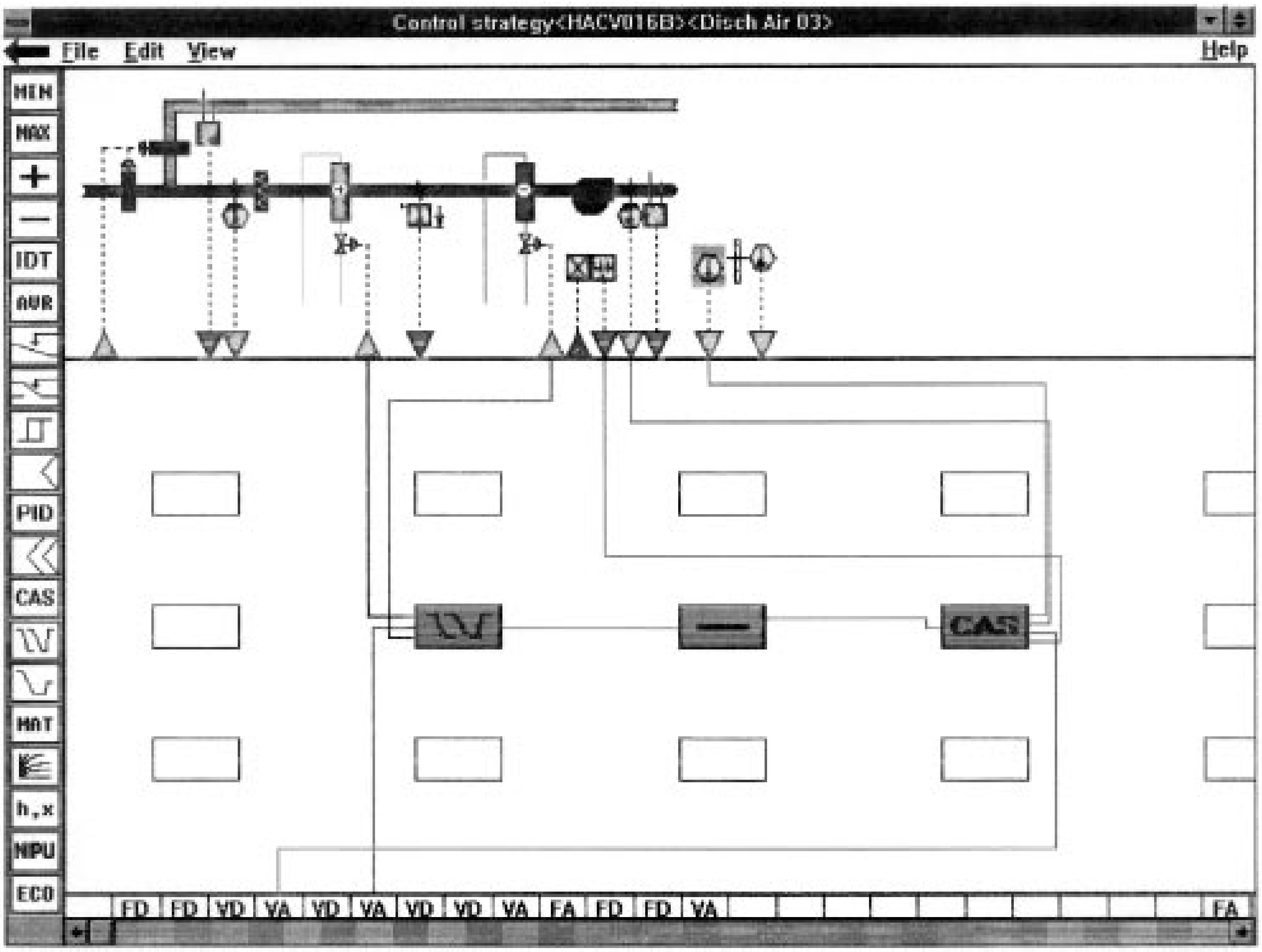


*Figure 6.*




It is important to determine the sensitivity of system response with the recommended KP, KI, and KD values as a function of changes of time constants of either the sensor (due to air velocity changes across the sensor) or the actuator (connection of other actuators to the same controller output). The overall recommendation to the installer includes these variations but are not discussed in this paper.

When fine tuning this control loop, the best guideline is to observe the period of oscillation. If it is small (less than one or two minutes), proportional gain is too high and should be decreased. When the period of oscillation is longer, integral time is probably too large. Using a derivative gain too large results in very fast oscillations or very erratic behavior. Using the derivative mode of control in a noisy environment may cause the same symptoms because of spikes in sensor input.

### Other HVAC System Simulations

Similar simulations are available for other typical HVAC processes such as discharge air from cooling and heating coils, static pressure control for Variable Air Volume (VAV) fan systems, return fan airflow, hot water converter, and space temperature (heating and cooling).

## SUPPORTING TOOLS

### Database for Configuration of PID Loops

After the recommended PID gains are known (from past experience or simulation analysis), they must go into the database of the control configuration tool. A variety of tools exists today, but Personal Computer (PC)-resident graphical tools are typical. They provide information to the control application engineer from windows available via mouse

*Figure 7.*

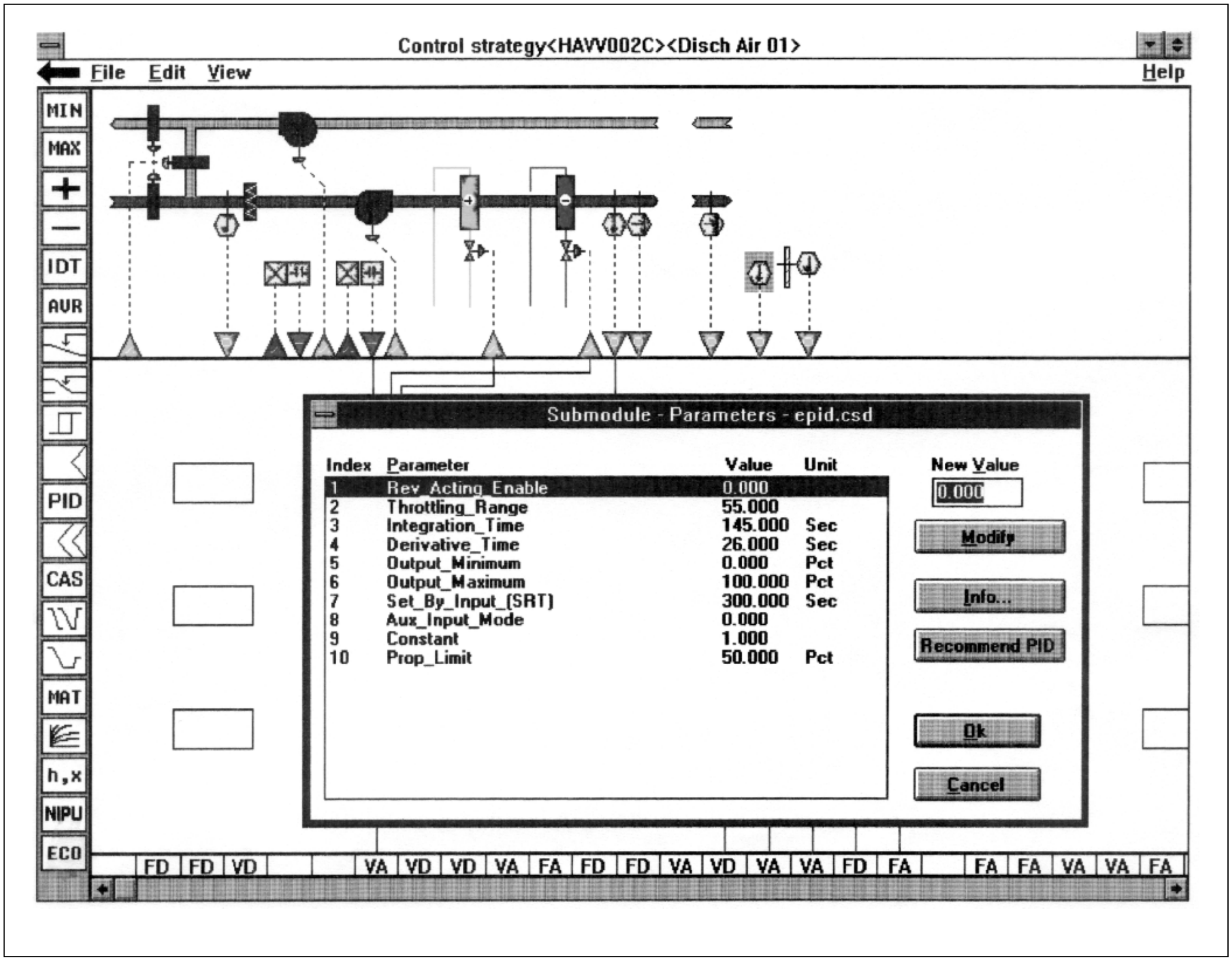
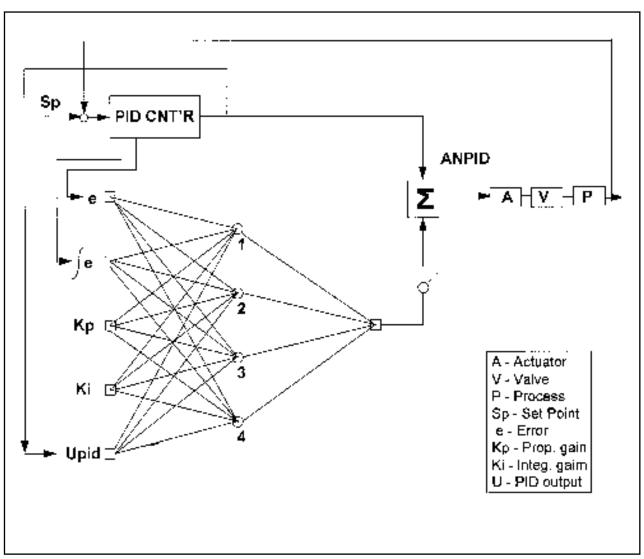


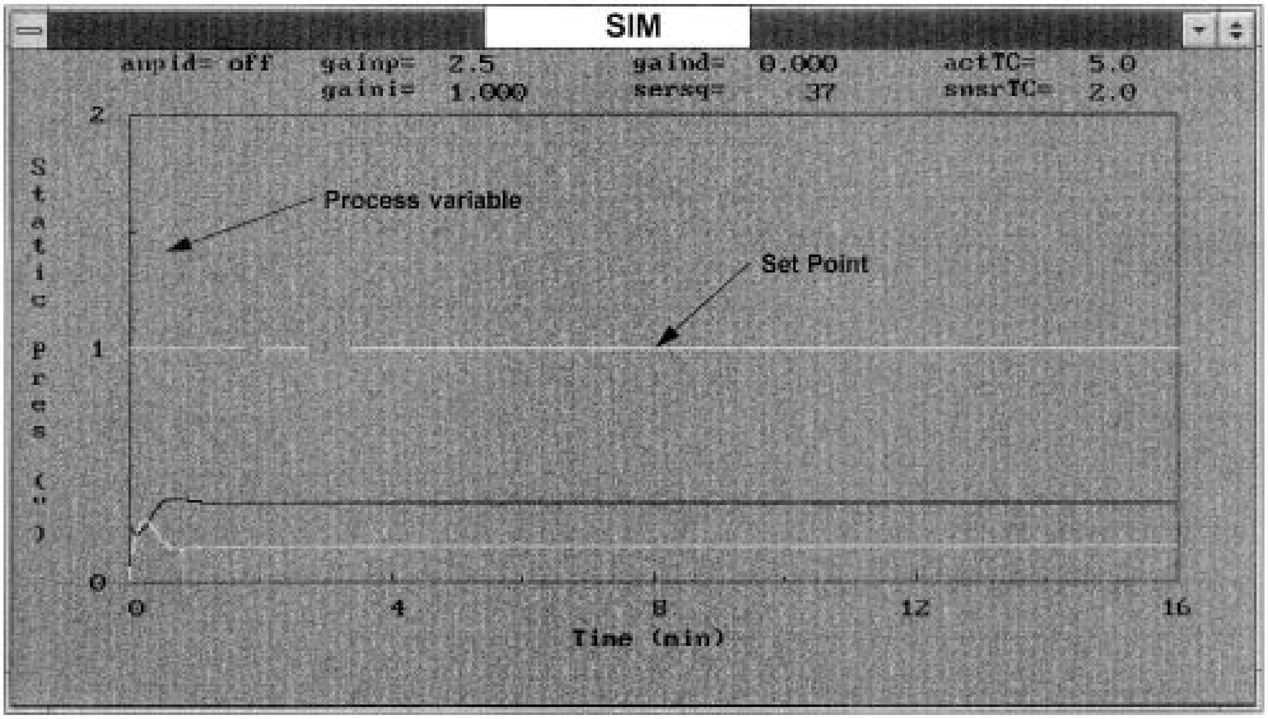

***Figure 8.*** *ANPID Controller*




clicks on a menu. Figure 6 shows a sample window. The top part of the screen shows the mechanical equipment. Below it are the sensors, valves, and actuators. Triangles show DDC program inputs (down triangle) and outputs (up triangle). The color of a triangle and any symbols within it further define point type (for example, circle within a triangle means analog point). Below the triangles is space for diagrams of control logic. The bottom of the screen shows the point types that go to the automation operator interface device.

Users display the information necessary to configure a controller by clicking on the controller icon. A menu allows them to modify any preset, recommended PID gains (see Figure 7). The configured database is down line loaded to the controller. Some of these tools are also used to verify whether the selected gains and the associated logic will perform properly.

*Figure 9a.*

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### Configuration Tool for Commissioning

During commissioning, the on-site engineer may need to fine tune the PID gain or verify operation of the controller. By connecting the configuration tool to the controller, the engineer can display real-time information associated with the triangles or with parts of the DDC logic. This information can help confirm the validity of the PID gains or the need to fine tune them.

## ADAPTATION/COMPENSATION OF THE PID LOOP WITH NEURAL-NETS

The draw back of the PID mode of control is that it was constructed to satisfy linear systems. However, in the building control applications the systems (plants) and control elements are not linear. Additionally, to distinguish from process control, there is daily load variation. For example, the summer cooling load in morning hours is low, in mid afternoon it is maximum and it decreases at late afternoon hours. Another issue facing the installer is the type and size of mechanical system to be controlled. The PID gains chosen are often set to minimize re-tuning and re-calibration trips to the site. The need to have a reliable adaptive algorithm to eliminate tuning cost is a key requirement in minimizing the cost of installation due to initial tuning and seasonal re-turning (changes in loads).

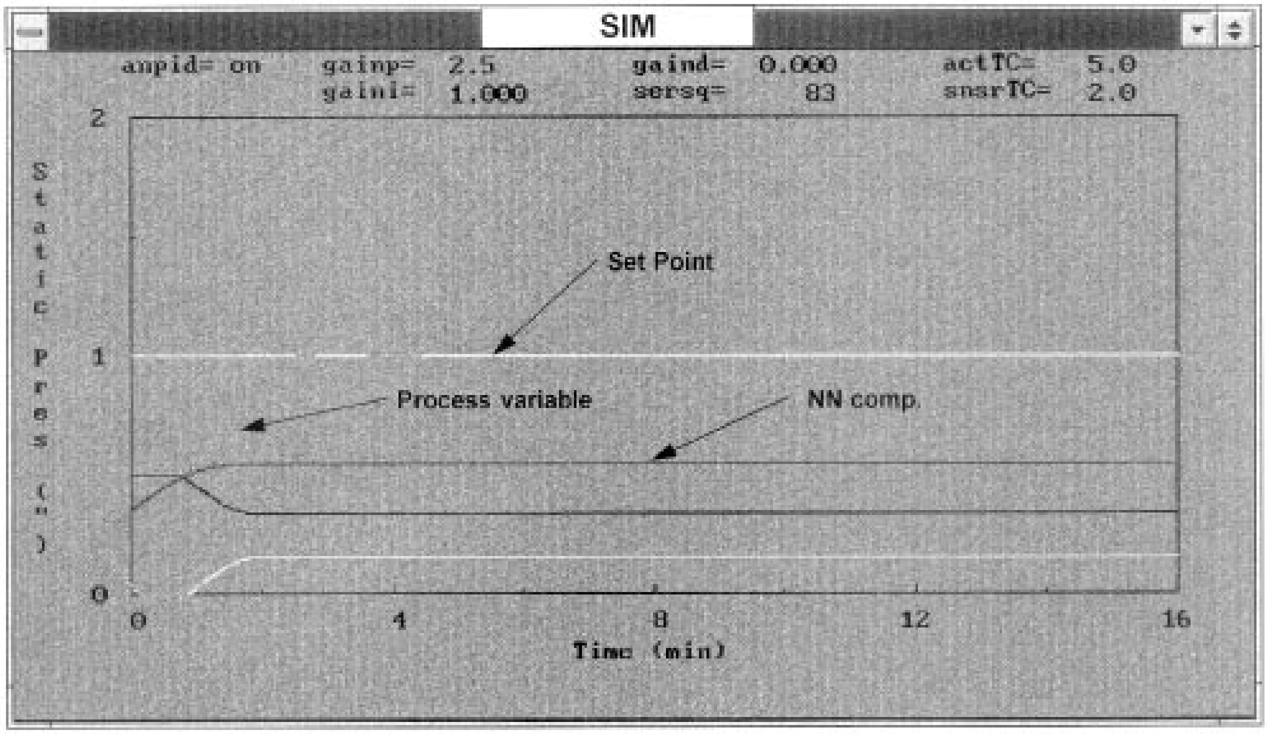
### Model Reference Adaptive control

One of the common adaptive control algorithms in the industrial process control arena is the Model Reference based adaptive control. In this algorithm a model of the plant and associated control elements exists and it is used to drive the actual PID loop output to follow the model. This approach is well suited the process control industry since there are many control engineers on site and they are proficient in modeling of the process. In the building industry, however, the building operators and the control installer have no such capabilities, thus it is always perceived as complex and requires added investment.

### Learning Algorithm for Adaptive Control

When information on the behavior of the process (plant) and the control elements is not available, it is desired to have an on-line learning algorithm to identify the process. The issue with process identification is that the algorithm *does not have the necessary start-up information*, therefore a special algorithm has to be developed. Some may use very

*Figure 9b.*




forgiving PID gain for the start-up operation. Another issue with this algorithm is that the *PID control algorithm does appear explicitly*. Thus, there is no specification of the PID gains. In many cases the implicit PID gain are not acceptable in the Building industry. The last issue with this algorithm is that *there is a need to specify a loop-time-step*. This loop-time-step is a function of the application and it is not always readily known.

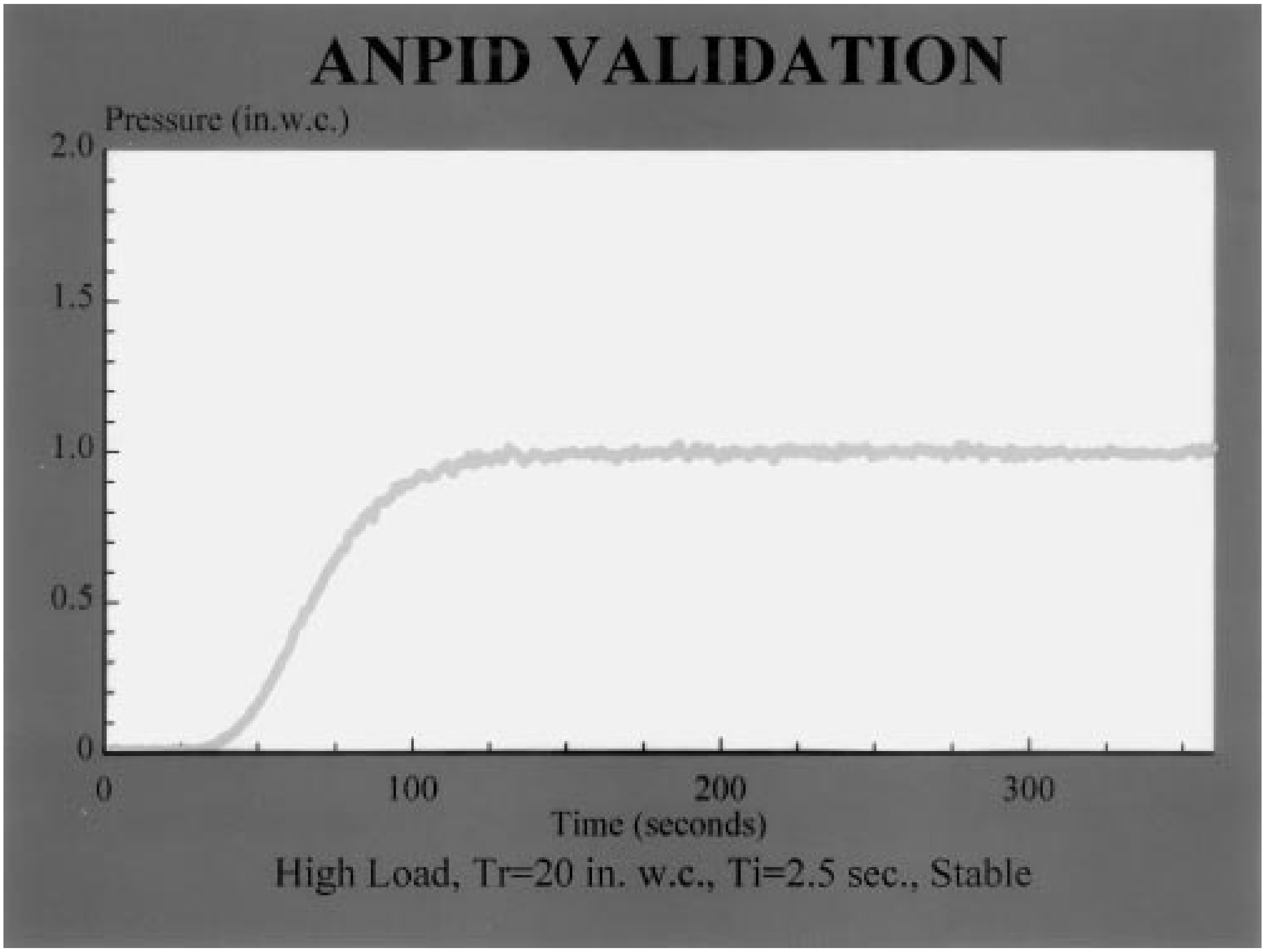
## Adaptive Neural Net based PID Control (ANPID)

The search for the best algorithms led to assessment of the artificial neural network technology to the application at hand. A neural network consists of several layers of ''neurons'' (nodes) that are connected to each other. A ''connection'' is a unique information transport link from one sending to one receiving neuron. Any number of input, output and hidden layer neurons can be used. One of the challenges of this technology is to construct a network with sufficient complexity to learn accurately so that the output is representing the response to all the input in their specified range of interest. This is accomplished by modeling the given system and using the results to train a neural network to minimize a desired cost function. The result of the training is a set of weights for the links between the neurons.

This technology is applicable to control of commercial building since one can train the neural net to predict behavior (say energy consumption) as a function of a few important variables (drybulb temperature, enthalpy of the outdoor air, supply air set point, solar load, etc.). The desire in a control application is to train the neural net to compensate the PID controller output as a function of the controller variables (error, integral of the error, Kp and Ki, and controller output) as function of the size of the system, Figure 8. The network is trained via simulation to minimize a cost function that includes: controller overshoot, settling time, deviation of feedback loop process, overall process error and standard deviation of the controller output.

The ANPID controller described above was trained for a static pressure control application. The controller was trained for a wide range of process static and dynamic gains, sensor and actuator time constants, and the desired range of Kp & Ki. The simulated PID loop is represented in Figure 9.a and for the ANPID controller in Figure 9.b. It clearly demonstrates that the PID loop has a start-up problem. The pressure overshoot can be catastrophic since it can rupture the ductwork. Therefore, the installer will use very wide throttling range (very low proportional gain) the have slow increase in static pressure. Whereas, the ANPID controller gets into control without (or with only minimal) overshoot. Figure

*Figure 10.*




10 represent the experimental behavior of the ANPID controller for static pressure control in an actual fan system.

## SUMMARY

The transition from pneumatic control to Electronic PID based control requires additional effort in tuning control loops, and caused the building industry to find interum solutions to help the installer to provide stable and efficient operation. A control configuration tool was enhanced with the capability to recommend initial PID gains. The same control configuration tool also included the capabilities to aid the installer with the commissioning and the control system as well as in fine tuning the PID loops. The search for tuningless algorithms led to the development of adaptive neural net based PID control in which the PID loop output is modified by the neural net control algorithms to extend the operation for wide range of process parameters.