DDC technologies are permitting a new flexibility in the traditional rules concerning the need for linear signals and responses with input/output devices

DIRECT DIGITAL CONTROL FUNDAMENTALS

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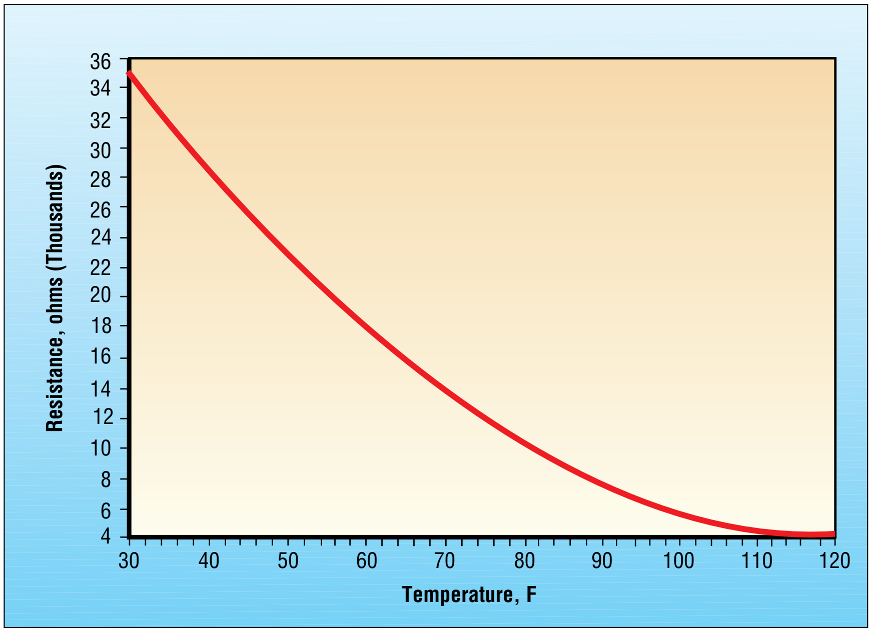
Ever since the energy crisis, when digital controls (then called EMCS for energy management and control systems) were unceremoniously ushered into widespread use for HVAC control, the industry has tried to make them look and act like the pneumatic controls they have superseded. Only occasionally are some of the profoundly expanded opportunities available with digital controls applied effectively. Furthermore, terms like *reset schedule* and *direct acting,* relevant only to pneumatic systems, are still commonly employed in what is now the digital controls era.

While the process of transition to digital control technologies tolerates this mixed bag, a multitude of new demands are requiring our industry to move ahead and realize the full potential of digital control technologies. Building occupants are demanding more comfortable and higher quality environments. Building owners continue to press for greater economies in construction, operation, and maintenance. Finally, a variety of pressures are upon us to provide more precise control and documentation that standards for temperature, ventilation, and indoor air quality are being met.

In this article, I will discuss how DDC technologies permit a new flexibility in the traditional rules concerning the need for linear signals and responses with input and output devices. When properly applied, this new flexibility can reduce the cost of DDC technologies. Next month, I will show how, by combining these fundamentals with emerging inter-manufacturer controls integration, designers can achieve new horizons in performance and energy efficiency.



1 Resistance curve for thermistor temperature sensor.

Why linear devices?

When pneumatic controls dominated our industry, building owners paid a high price for modulating loop performance and stability. One of the prices paid was the requirement that input and output devices be linear with respect to the system variable they sensed or controlled. This need for linear response was essential to match the limited control capabilities of pneumatic controllers. A number of rules and conventions were established within our industry that made achieving this linear response requirement easier. Among these were the development of the equal percentage valve, which included the seemingly backwards rule of thumb that called for sizing control valves smaller than the pipe size. Similarly, mechanical sensing devices were constructed to provide linear change in control air pressure over their entire sensing range.

While these conventions and rules of thumb served the days of pneumatics, they now need to be rethought. Requiring what I call external linearization in digital control designs adds costs in two ways. Linear devices are often more expensive than nonlinear devices that may offer improved levels of performance in DDC applications. Further, linear output conventions, such as designing a high pressure drop through valves or dampers, carry a substantial continuous operating energy penalty. By developing new rules and conventions, the knowledgeable designer can produce designs that have lower first and operating costs and may operate more reliably as well.

Linear devices in the DDC era

The need for linear response in modulating control loops has not been eliminated by the introduction of digital controls. While digital controls offer improved modulating control capabilities, including proportional/integral/derivative (PID) controllers, these control loops continue to be based on the principle of linear response, at least over certain ranges. However, in most typical applications, digital controls can easily internally linearize both input signals and output control functions.

Internal linearization of inputs

One way to reduce the cost of some DDC configurations is to permit nonlinear input devices and use the DDC system for scaling to achieve the correct reading over the range required for the application. I continue to see DDC specifications that limit the selection of input devices to those that provide a linear signal to the DDC system over a wide range of values. Except in special cases, this is an unnecessary requirement that adds costs and may cause other problems. Consider temperature sensors. Fig. 1 shows a resistance curve for an inexpensive thermistor type temperature sensor that may be employed for room temperature sensing. Thermistors are excellent choices for HVAC applications. They are inexpensive, have excellent accuracy and very low hysteresis, and respond quickly to temperature changes. Furthermore, at temperatures normally involved in HVAC applications, thermistors have excellent long-term stability (some care should be taken in choosing thermistors when temperature may rise above 240 F). Finally, because thermistors are typically high resistance (10,000 ohms is typical), they are not affected by variations in wiring distances. However, some designers continue to exclude thermistors because the input signal is not linear with temperature over wide temperature ranges. Instead, low impedance RTD type sensors are often specified. This type of sensor typically requires an electric circuit at the sensor that linearizes and transmits the signal in a way that it will not be affected by wiring resistance (usually a current loop signal is used).

Employing low resistance RTD sensors with additional electronics presents a number of potential problems in DDC applications. First is the matter of accuracy. While the RTD sensors themselves provide excellent accuracy, it is not uncommon to find *end-to-end* accuracies (I use *end-to-end* as the comparison of the value read by a precision thermometer at the device compared with the actual reading at the DDC system operator's terminal) out of tolerance. Calibration of the current loop input may be more difficult than that of a simple resistance type thermistor.

Other potential problems with RTDs range from the additional electronics (usually located at the device) that may complicate reliability issues all the way to how the

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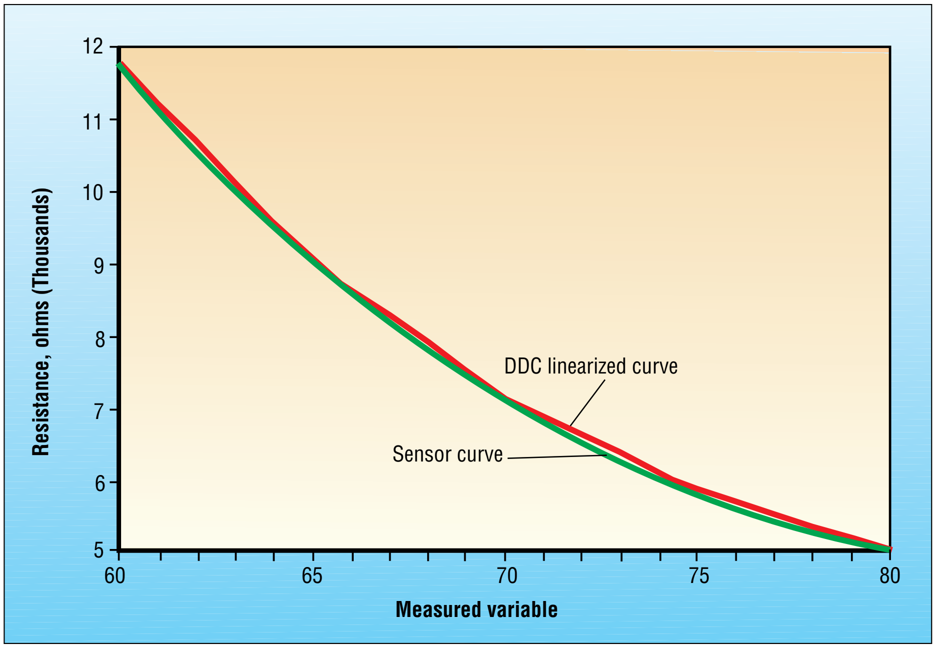

2 Nonlinear sensor resistance curve. The sensor performance curve is a smooth curve over the sensor's operating pressure. The DDC linearized curve is a series of straight lines that closely approximates the sensor's performance.

continued from page 64

sensor and electronics are configured, which on occasion has been found to affect adversely the sensor signal.

Table functions that are now readily available with DDC products can be employed to scale thermistors and other nonlinear devices over a wide range of values. Fig. 2 shows how a DDC system can linearize a continuous, nonlinear sensor input curve with a table function. A number of straight line curves are established in the table function to approximate closely the nonlinear function of the device. As long as simple, inexpensive devices can meet the repeatability, hysteresis, and stability requirements for an HVAC application, such devices should not be rejected because their signals are not linear.

Is linear output required?

Once it is understood that input devices need not be linear, it is not a great leap to recognize that the response from output devices controlled by analog outputs similarly need not be linear. However, the issues here are more complex and more ingrained in the rules of thumb that engineers frequently apply automatically, so some in-depth discussion is required.

Because of the pneumatic background, valve design manuals commonly stress the need to select coil/valve combinations for which equal increments in valve position will effect equal increments in heat transfer of a typical heating or cooling coil throughout the stroke of the valve actuator. Fig. 3 shows how traditional design practice seeks to linearize the overall performance of valve and cooling coil. Carefully selecting a coil and valve combination can provide nearly linear performance over the entire range of load possibilities. Such selection is done because it is assumed that the valve will be operated by a controller with a fixed proportional gain. Though this design principle is still widely employed, it is no longer applicable in many modern HVAC applications. In VAV cooling coil applications, the variations of air flow and air/chilled water temperature characteristics act to change dynamically the heat transfer characteristics of the valve/coil arrangement as these parameters change. This makes it very difficult to select a valve/coil combination that will be linear through the variety of conditions that may accompany its operation.

The higher performance of DDC systems permits designers much greater flexibility in the design of modulating controls without establishing static (and therefore unrealistic) design criteria. Fig. 4 shows a valve and coil combination that does not provide a linear response of valve position to coil capacity. However, modern DDC systems permit scaling tables to be applied to analog outputs as well as the inputs. Output scaling permits an inherently nonlinear device combination to respond in a linear fashion to signals from the DDC system. In this example, the valve and coil combination provides about 70 percent of the design cooling capacity at about 20 percent valve travel. The DDC output to the valve can be adjusted with the scaling table to position the valve at 20 percent

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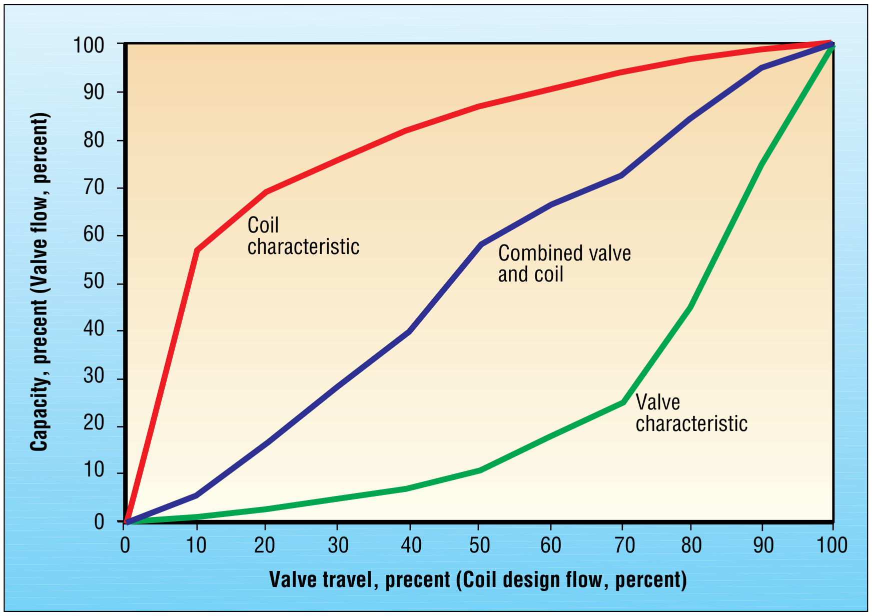
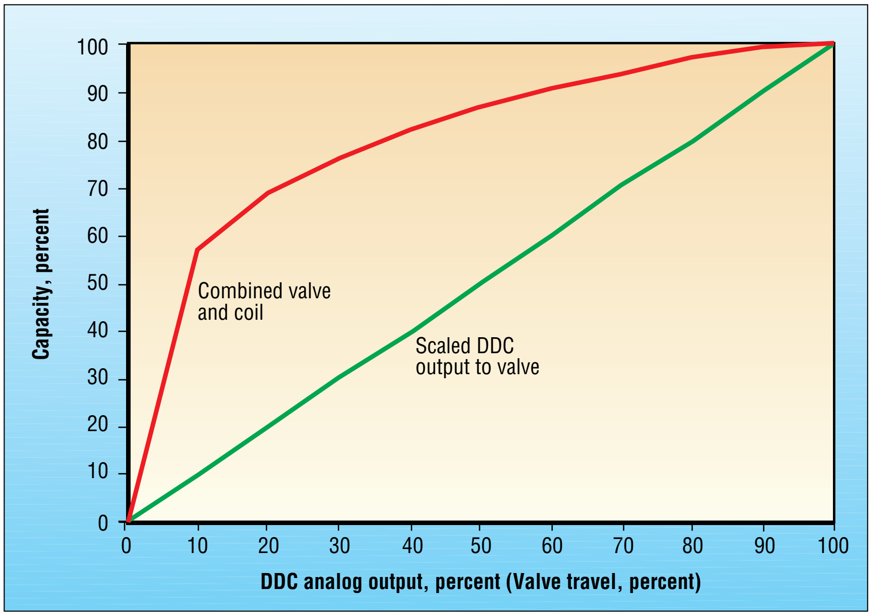


3 Design of chilled water valve and coil combinations for proportional control.



4 Use of scaling to linearize control for DDC control.

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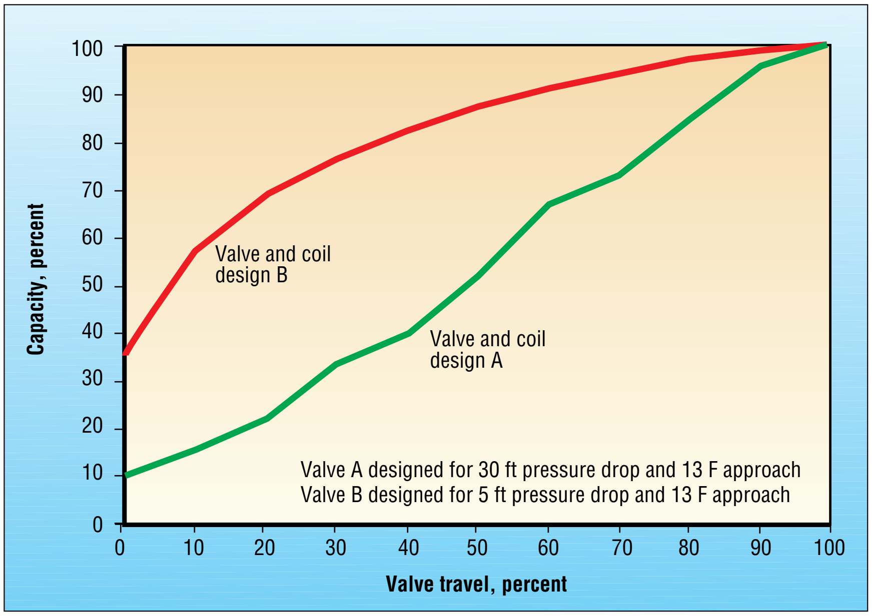
travel at a 70 percent output signal from the DDC system. The scaling factor allows standard PID control to operate the valve effectively because of a software linearization of the valve/coil combination.

However, the chilled water flow and heat transfer performance assumed for Fig. 4 is valid only for constant load-side flows and inlet temperatures and for constant chilled water supply temperatures. Whether inherent in the system design or for optimization reasons, rarely in real HVAC applications do these other variables remain constant as control loops operate. As previously discussed, the issue of linear output combinations has therefore been only weakly resolved in the past by attempting to linearize components at one set of system conditions. Obtaining good control over wide ranges of system conditions can be resolved far more completely and effectively with the higher performance capabilities of DDC systems. The proportional, integral, and derivative gains can be tied to algorithms that adjust their values as the variables such as load-side flow, temperatures, and chilled water temperature change. Even more impressive is the emergence of self-tuning controllers. These controllers continually re-establish the various gains associated with a control loop to provide continuously precise control without hunting. The benefits of self-tuning are especially important because variables beyond the immediate control loop can have profound and widely varying effects on each control loop. Self-tuning features are becoming widely available with DDC systems and are enormously effective in adjusting control loops to continue stable operation as other system variables change.



5 Design of valve and coil combinations for proportional control.

Controllability

As previously discussed, selecting equipment for linear response should not be an overriding consideration for designers in this era of digital controls. However, this does not mean designers can be imprecise in their designs or in the selection of control loop components. The issue of controllability is one that will continue to play a prominent role both in the design of systems and the selection of individual components. Controllability remains largely a sizing issue. If a valve is oversized for given conditions such that the smallest increment possible from the control loop will substantially overshoot the desired control conditions, the loop has become uncontrollable. This is a problem that typically emerges during periods of low load. Fully understanding the issue of controllability and applying DDC capabilities correctly allows designers to solve such problems and at the same time vastly improve the efficiency and performance of these systems.

Selecting a control valve with a lower pressure drop will reduce the pumping power required to meet the load conditions. Traditional practice strongly condemns the idea of employing large valves with lower pressure drops because of the nonlinear response and the lack of controllability at low loads. Fig. 5 illustrates the dilemma. The valve/coil combination with Valve A may be selected according to traditional design practice because it is reasonably controllable at low loads. The vertical axis intercept represents the smallest incremental cooling transfer possible as the valve is cracked open. Note that it is small—only about 10 percent of the design maximum cooling rate. The coil combination with Valve B has a much lower pressure drop because Valve B is a larger size valve. While valve/coil Combination B would require less pumping power, the Y-axis intercept is much higher than that for Combination A. Traditional design criteria typically declare Valve B unsuitable for the application because it is uncontrollable at lower loads and the valve position/cooling capacity relationship is nonlinear. But when it is integrated with a high-performance control system that can adjust both the chilled water temperature and the loop head pressure, will linearity and controllability of Combination B really be a problem?

System dynamics

To see how this question can be answered, consider the graphs in Figs. 6 and 7. Fig. 6 shows the operation curves for valve/coil Combination B at a number of different approach (chilled water supply less air temperature leaving coil) temperature conditions. It is clear that increasing the chilled water temperature relative to the leaving air temperature markedly improves the con-

continued on page 70

continued from page 68

trollability at low loads. Similarly, Fig. 7 illustrates that the decrease in pressure across the valve/coil combination also improves the controllability at low loads.

Designers can use these relationships to reduce substantially the problem of controllability. At periods of uniform low loads, the DDC system can reduce the head pressure across a valve and increase the chilled water temperature to improve controllability. If all valves on a common chilled water loop experience similar decreases in load concurrently, as is typical in many HVAC applications, this parameter adjustment is a great help in improving controllability at low loads.

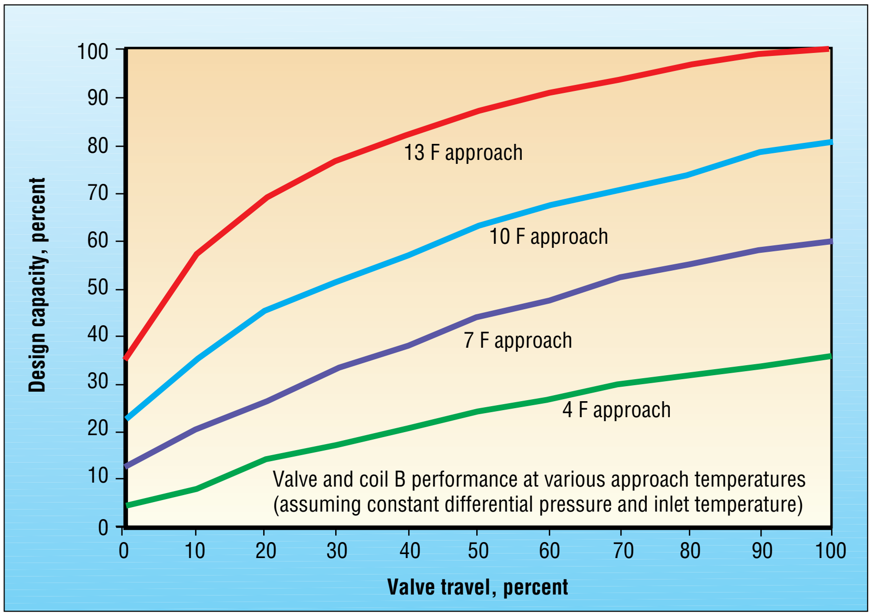
It is apparent from the two figures that larger rangeability and low load controllability are achieved by controlling the chilled water temperature for load adjustment. Raising the chilled water temperature provides a bonus of chiller efficiency increases, but chilled water adjustment reduces pumping savings because a higher chilled water temperature increases the water flow necessary to meet loads. Additionally, under certain circumstances dehumidification requirements may limit the permissible chilled water adjustment.

Exploiting the integrated control capabilities of DDC systems and controlling chilled water temperature and hydronic loop pressure in coordination with the control valves allows valve/coil Combination B to perform very well in many HVAC applications.

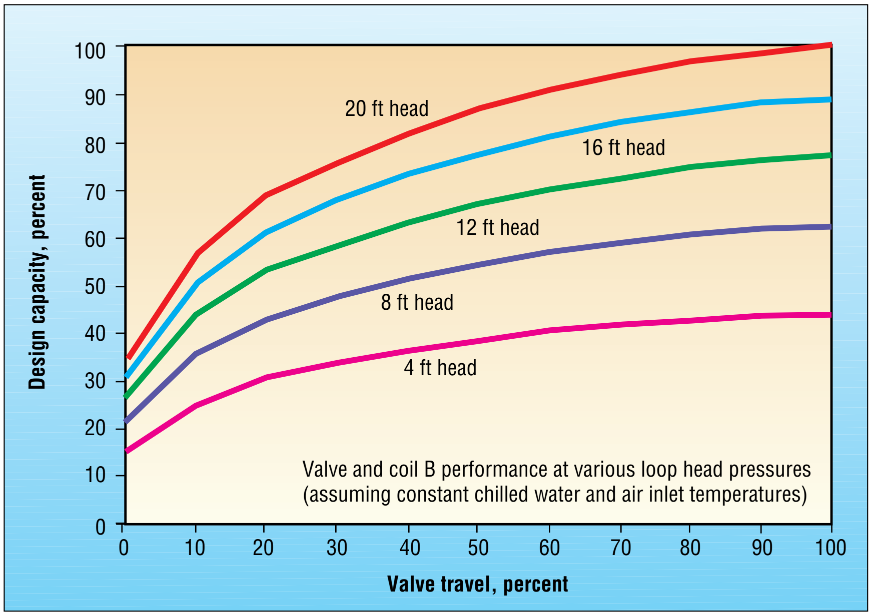
Next month we will focus on the level of integration required to make valve/coil Configuration B operate effectively. We will discuss integrating the operation of the various equipment involved in providing comfort, possible now through the industry moves to provide communication bridges among manufacturers. By concentrating on selecting the most cost-effective input/output devices and by utilizing the emerging communications pathways between equipment from various suppliers, we will see that new horizons of performance and energy efficiency can be attained with simple and economical controls configurations.

Summary and conclusion

Designers must exploit the benefits of higher performing DDC systems to develop an understanding of the fundamentals of interfacing hardware points to DDC systems. In so doing, a more in-depth look into total system operation must be evaluated before solutions are selected. Simply following traditional rules of thumb regarding linear input and output devices is a poor design practice in this digital controls era. Ω



6 Heat transfer vs. valve travel for various approaches (leaving air temperature minus entering water temperature).



7 Heat transfer vs. valve travel for various loop head pressures.