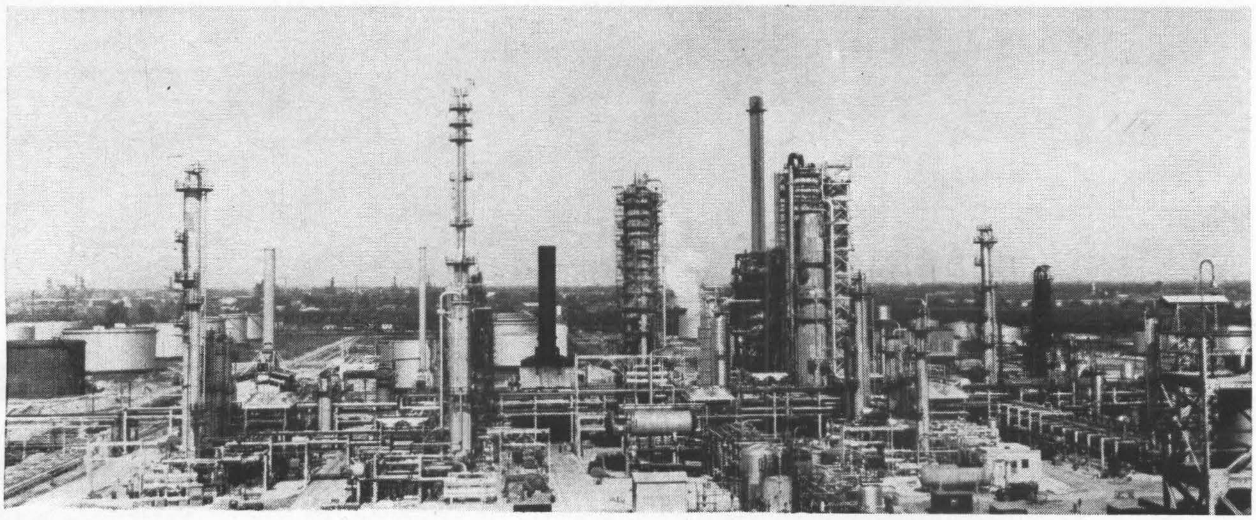

Process industries, typified by this petroleum refinery operated by Standard Oil of Ohio at Toledo, will benefit most from Direct Digital Control. These industries have long experience in multi-loop, although conventional, process control

Direct digital control at the threshold

A new concept of control, with a centralized special purpose digital computer instead of separate analog devices, may finally win widespread acceptance for electronic process control. The direct digital controller is simpler than a process control computer and needs no complex programming

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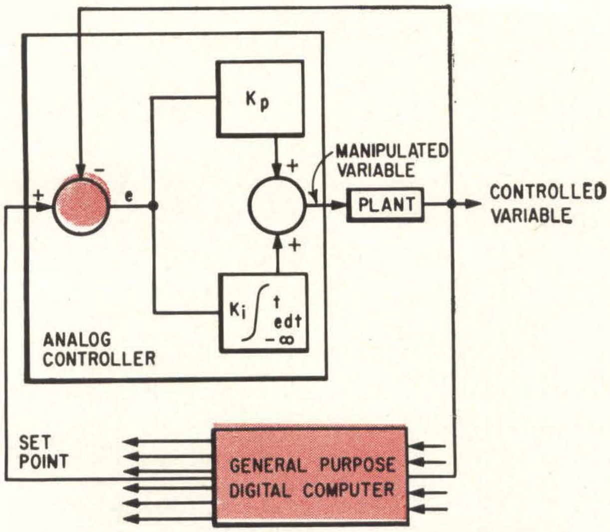
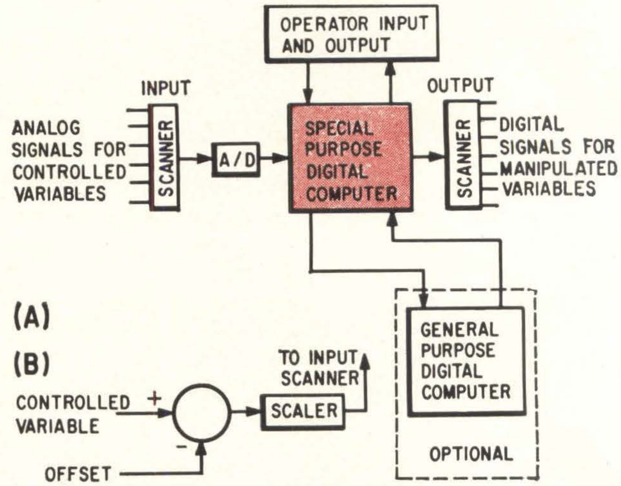
Traditionally, industrial process control has used pneumatic instruments and controls. Only within the past seven years have electronic devices made a dent and what they have done has been disappointing. Although electronic instruments and controls have worked satisfactorily, they have not proven out economically in many applications. Now a new concept, Direct Digital Control (DDC), may change all this. Direct digital control of processes will allow tighter operation, regulated by simple, relatively inexpensive, special purpose digital computers. It does not require a large investment of time and money for computer programming.

Most often, process control means regulating or maintaining several hundred variables at predeter-



Computer process control at present is complex. Diagrammed is one control loop of a general purpose digital computer controlled process



Direct digital control replaces conventional analog controllers with one time-shared special purpose digital computer, using an optional general purpose computer for process optimization as in A. Inset B shows signal offset and scaling relationships

mined values. Each parameter is regulated with a conventional analog controller, or many may be controlled by a single process control computer. Both approaches work but are either inadequate or too expensive when an engineer wants to optimize the process rather than just control it.

In a conventional (using an analog controller) control system, the variables (pressure, temperature, flow, speed, rate, liquid-level and the like) are continuously sensed and subtracted from a set-point (or reference) to produce an error signal. This signal is amplified and used to manipulate the variable to decrease the error.

To this conventional control system, designer's are adding a general purpose, high-speed digital computer with analog-to-digital (A/D) and digital-to-analog) (D/A) converters as shown above, on the left. Process variables are sampled, quantized, and fed to the computer which monitors the variables and prints out records of process performance. In addition, the digital computer often uses a mathematical model of the process, together with analytic performance criteria, to determine optimal operating conditions (set-points). These set-points are converted to analog signals and transmitted to the analog controllers, either automatically or through an operator.

DDC of processes

Direct Digital Control is an intermediate step replacing a group of analog controllers with a single, time-shared, special purpose digital computer. This DDC computer duplicates the analog controller's actions while providing easy communication with an operator and/or a general purpose digital computer.

The function of the DDC computer is shown in the simplified diagram above right. At the left of the diagram are shown some controlled variables. Transducers sense each, producing an electrical signal which is offset and scaled (that is, zero-reference set at a convenient level for the range of signals expected and the resulting signal scaled in magnitude as indicated in insert B). The scanner samples each input channel in turn and applies the signal to an A/D converter which quantizes the signal and transmits the result to the DDC computer. Stored within this computer are the set-points, previous error for each variable and allowable limits. The variable is first checked to determine if it exceeds allowable limits; if it does an alarm is sounded and control is returned to the operator. If the variable is within limits, the DDC computer subtracts the variable from the set-point to determine the present variable error and using the previous value of error, computes a new value of the manipulated variable from an appropriate algorithm.

Parameters for each control loop are stored in the computer memory and used in the algorithm for computing manipulated variables. Because these are stored as numbers (not limited, as in an analog device, by the physical limits of a potentiometer or capacitive device) the parameters of the controllers may be varied over a much wider range than in actual analog controllers. Moreover, the parameters can be changed individually (because they are separate numbers) without the interaction problems often encountered in analog controllers with their input dials. The new value of the manipulated variable is transmitted to a digital actuator which drives the variable to the new value. The output scanner connects the DDC computer output to the proper actuator.

Input-output devices

Two other input-output devices are available, a manual station controlled by an operator and a general purpose digital computer. The manual station allows the operator to call for special print-outs of selected variables, to supply new set-points, or to change the DDC computer parameters, that is, the constants used in the algorithm for a particular variable. In addition, the operator may over-ride the DDC computer assuming control when conditions warrant.

The other input-output device is a general purpose digital computer. Its normal function may be the processing of payroll records, engineering calculations, etc., but it is also used to communicate with the DDC computer for starting up the process, shutting it down, controlling the system during alarm situations, or for process optimization.

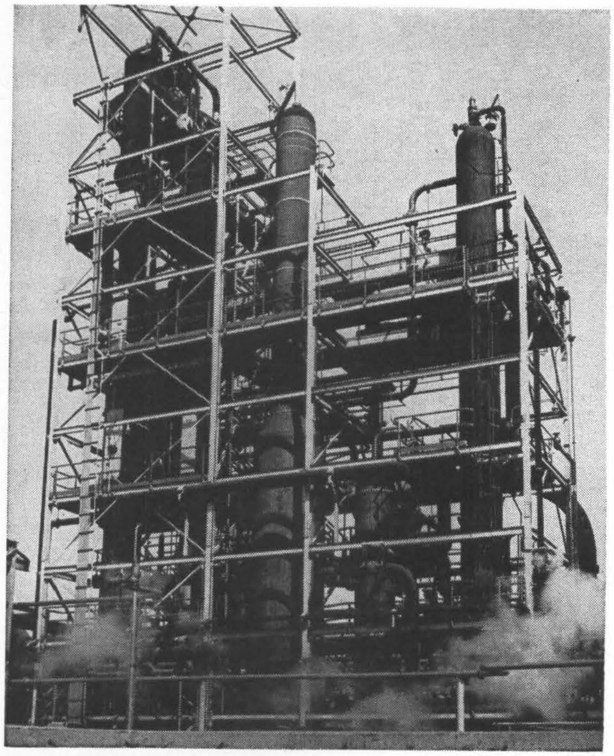
Actual application

Direct digital control has been simulated by several companies and at least one has tried it on an actual process[1, 3, 4, 5]. Involved in these simulations were Corning Glass, Conoflow Corporation, Monsanto Chemical, Leeds and Northrup, Westinghouse Electric, TRW (Bunker-Ramo), Foxboro and others. In these studies, single loop processes with various types of elements were simulated on either a digital or hybrid computer and DDC evaluated using signal rise time, overshoot, and other criteria.

The result was general agreement on minimum sampling intervals for typical process variables of 1 second for flow, 5 seconds for pressure, and 10 seconds for temperature variables. Thus for a process of approximately 200 loops, the required scanning rate is well within the state of the art, being approximately 150 points per second for a 200 loop controller with a typical distribution of the variables among flow, pressure, etc.

One of these experiments by Monsanto Chemical Company and Bunker-Ramo, applied DDC to an operating plant in the separations section of Monsanto's ethylene facility at Texas City, Texas.[1] Since a DDC computer was not available, it was simulated on a more conventional (RW 300) process control computer. The distillation column (pictured right) had 10 control loops including temperature, pressure, and flow variables. The 10 variables were each sampled once per second and the data transmitted to the computer. The corresponding manipulated variables were calculated using a discrete version (error values sampled at equal intervals of time rather than on a continuous basis) of the proportional-plus-integral (P-I) control algorithm.

Results indicate that all ten loops responded at least as well as with conventional analog controllers and in most cases gave a smoother and faster response. This improvement was traced to the noninteracting parameters of the digital controller, and the fact that these parameters could be adjusted much more exactly than in the analog controller. As a result of this study, it was estimated that the saving in capital investment for a 200 loop direct digital control system would lie between $500 and $1000 per loop. (One industry spokesman has stated that, concerning cost, possibly 50 loops can be the break-even point—Ed.)



Experimental DDC was tried in Monsanto Chemical's Texas City, Texas, ethylene plant, controlling 10 loops on this distillation column. Savings for a similar 200 loop system were estimated at 500 to 1,000 dollars per loop less than for conventionally equipped loops

Benefits to industry

Industries benefiting most from DDC will be those which are already experienced in multi-loop conventional process control. These include steel, petroleum, glass, chemical processing, food, and electrical utilities. Other processing industries which have much to gain from better control, such as paper, are retarded by the lack of adequate automatic measuring instruments for critical process variables.

The principal benefits of DDC are both immediate and potential. They include: lower capital investment by replacing many analog controllers and recorders with one time-shared DDC computer; better control because each controller parameter can be changed over a wider range than can the corresponding parameter of an analog controller, and in addition, the controller parameters are noninteracting (can be changed independently) and can be varied in a much smoother manner; straightforward data logging because the desired data is present in a single location, in digital form, and may easily be printed out for a permanent record or displayed for an operator; ease of communication with a general purpose digital computer which need not be tied up 100% of the time on the process, but used only as needed by the operator; ease of automatic start-up and shut-down by a general purpose computer communicating with the DDC computer; and, potentially improved control algorithms such as non-interacting control, non-linear control, and the like.

Experience with the present generation of digital process computers indicates most of the cost of implementing computer control lies in determining an adequate mathematical model of the process and in the programming of the computer, rather than in the hardware itself. This is mainly because those processes which can best profit from computer control are mathematically the most complex and least understood. Consequently, a computer is often added to a process initially for data gathering and model building purposes even before it can be economically justified.

DDC allows economical data gathering for model building purposes. Then, when the process is well understood, a general purpose computer (either on or off line) can communicate with the DDC computer to optimize set-points, controller settings, and even dynamic response.

Hardware requirements

Potential users of DDC are essentially in agreement as to the requirements for a DDC computer. Monsanto Chemical, Corning Glass, and the DuPont Company at a recent conference listed their requirements. These include a reliability or availability of 99.95% (4 hours down time per year). Several types of outputs are also needed including dc for driving conventional pneumatic actuators, pulses for devices such as stepping motors, and a pulse whose width is proportional to the output signal and which can then be integrated by an output advice such as a motor.

Many companies are readying equipment for DDC but details are still proprietary. In recent months, two companies have announced equipment for direct digital control. The first, Minnesota Mining and Manufacturing, displayed a controller at the September ISA show in Chicago. This controller will be available for use with 8 to 32 loops. Claims are that it will be economically competitive at 20-30 loops. Outputs of this unit are low current signals for driving conventional actuators. The other user desired outputs are not available.

The Westinghouse Electric Corporation is going to install DDC at a unit of Commonwealth Edison in Chicago for control of all boiler loops.[9] A control computer is used as the DDC computer to scan the inputs, convert them to digital signals and process them. The algorithm for each control loop is programmed and can be either simple or complex depending upon need. This is in contrast to the 3M special purpose DDC computer discussed above which does not permit programming of the individual loop algorithms. The Westinghouse system will also provide all of the types of outputs discussed above. Their more complex computer allows a pre-programmed operation which will depend upon operating level. Computer control parameters in the DDC algorithms will be changed as the operating conditions of the boilers change. (The program for this installation resulted from a detailed IBM 7090 computer study of Commonwealth Edison's boiler system).

Problems

One point of unanimity among potential users of DDC is that the computer must be at least as reliable as existing analog controllers. This poses the problem that failure of the computer can cause the shut-down of the entire process together with the production of much off-quality product. (This is in contrast to only one loop going out if an analog controller is downed.) To achieve the required 99.95% availability demanded by users, reliability of presently available computers must be increased by an order of magnitude. This is within the state of the art.

A second problem is the digital actuator on the output side of the DDC computer. Conventional analog pneumatic valve actuators are very reliable and economic but they require the computer to supply a dc signal. This signal is first converted by a current-to-pneumatic transducer to an air signal which is then applied to the actuator. This requires each such channel have an analog memory which stores the signal between successive outputs.

Output actuators which are actually digital would not need this analog memory. For example, some development has been achieved on actuators which accept a binary-coded signal, each bit entering on a single line.[6] This binary signal drives the digital actuator directly without converting the signal to analog form. At the recent IFAC (International Federation on Automatic Control) Congress in Basle, Switzerland, a digital valve was demonstrated by the Lignes Télégraphiques and Téléphoniques of Paris, France. It was actuated by digital signals, each bit of which controlled a single solenoid. American companies judged this particular valve too expensive for general use, but it is indicative of the direction in which actuator research is headed.

Another attractive output actuator is the stepping motor, which is capable of stepping to any one of a large number of discrete angular positions and remaining there until further input signals are received. The motor steps one position for each pulse received, the direction being determined by which of two lines received the pulse as shown at the top of p 53. Stepping motors are available from several manufacturers in a variety of sizes.

An example: the SLO-SYN motor made by Superior Electric Company. It is capable of rotating at about 200 steps per second maximum or approximately 72 RPM. With such a motor as the output device, the DDC computer supplies the correct number of pulses during each sampling interval to change the manipulated variable by the desired amount. One way is to run the motor at maximum velocity over a portion of the interval; another is to run at minimum velocity over the entire interval. The former seems to be simpler to implement.

The stepping motor can also be used in a variety of applications other than opening and closing valves. For example, it may rotate the shaft of a potentiometer or rheostat thereby controlling voltage or current flow. This can alter the firing angle of a bank of silicon controlled rectifiers or the bias of a magnetic amplifier to control the speed of a motor. The rotary motion can also be converted to linear motion by conventional devices.

DDC computer structure

A study of DDC was initiated at Case Institute of Technology several years ago. Out of this initial study has come one design for a DDC computer using stepping motors as actuators. This system's design illustrates the general principles governing a DDC computer with this type of actuator.

Conventional analog controllers produce an output signal which is a linear combination of the input error (proportional control), the derivative of the error (rate control) and the integral of the error (reset control) which is

$$m(t) = K_p e(t) + K_d \frac{de(t)}{dt} + K_i \int_0^t e(t)dt \qquad (1)$$

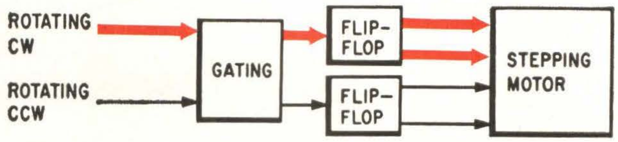
where m(t) is the manipulated variable, the output of the controller. Simulation of direct digital control indicates that adequate control can be achieved using only the proportional and integral control functions. In fact, the addition of the derivative function in digital form makes the control unduly sensitive to noise and quantization errors. Using standard sampled-data theory, a digital approximation to Eq. 1 with $K_d = 0$ is found to be

$$\Delta m_n = Ae_{n-1} + Be_n \qquad (2)$$

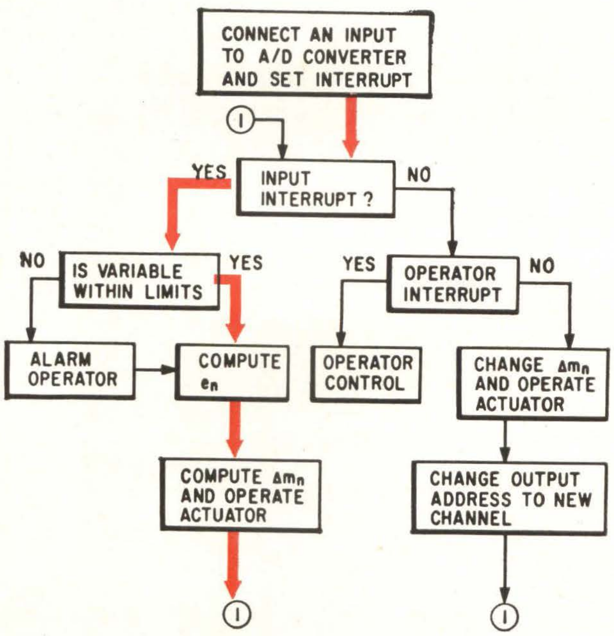
where Δm_n is the change in the manipulated variable, e_{n-1} is the previous value of error, e_n is the present value of error in the controlled variable, and the constants A and B are functions of the controller parameters K_p, and K_i and the sampling interval.

The function of the DDC computer is to evaluate changes in the variables using Eq. 2 repeatedly for each controlled variable. Thus, the same simple computations are repeated over and over, the only differences between calculations for successive channels are the constants and error signal. As a consequence, no programming of the computer is necessary to use it to control a process. Because of this, the internal structure of the DDC computer can be much simpler and less costly than for a general purpose machine.

When stepping motors are used as the digital actuators, the number of pulses required to effect a change in the variable is linearly related to Δm_n and hence can be incorporated into the constants A and B. That is, the quantity calculated in Eq. 2 can be the number of pulses needed with no conversion required. If the input to a digital actuator



Output actuators which are actually digital, such as this stepping motor control, need no memories as do analog pneumatic valve actuators



DDC computer operation is shown in this flow chart. Improved process control results from wider adjustment range and non-interacting parameters of signals

The authors

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James D. Schoeffler joined Case's faculty four years ago after receiving his doctorate from M.I.T. An Associate Professor of Engineering, he is also a member of the Control of Complex Systems Group. Currently he is doing research in the systems aspects of modeling, optimization and multi-level control.

Compactness of DDC will replace such massive nerve centers as this Central Control House at Sohio's Toledo Refinery. Instrumented 96-foot curved panel controls processing loops and catalytic cracking and steam generation

is the actual digitally coded variable, then m_n is calculated from Δm_n by adding the previous value of the variable to it before transmission to the output.

With the DDC computer shown on page 50 the information entering the registers of the computer from the input scanner is a digitized representation of the measured variable.

The drawing also shows an A/D converter, but there is considerable research and development under way towards producing a digital signal directly at the measuring instrument. From the viewpoint of transmitting information by wire for distances of possibly up to a mile, in a situation where the chances for interference pick-up are good, the digitized version is superior to the analog. Because it is uneconomical to have an electronic A/D converter at each measuring instrument, development is being pressed for a family of digital sensors for pressure, temperature, flow and the rest.

The scanner generally scans in an interlaced pattern under control of the computer. The computer keeps track of the variable being scanned so that it may be entered correctly into the computer memory.

The input scanner is usually a relay switching matrix. Its switching time is long, compared to the time required for the computer to perform the arithmetic calculations. There is also a time delay required for the transients in the A/D converter to decay. The net result is that the computer can do other operations while waiting for the next read-in operation to occur.

Operation of the computer can be summarized by the flow chart on page 53. During each one second interval, the computer rapidly scans the output channels. When an input channel has been sampled, quantized, and the transient in the A/D converter has disappeared, an interrupt signal causes the machine to stop scanning the output lines and to take the input signal and process it. This involves calling the appropriate data for that channel out of memory, checking the variable to insure that it is within allowable limits, and signaling an alarm if it is not. Assuming it is within limits, the variable is substracted from the set-point (stored in memory) to form the present error. This error and the constants in memory are used with the digital approximation of the proportional-plus-integral algorithm to calculate a new count-down word. This word together with the present error are then stored again in memory and the computer returns to output scanning until interrupted again by the next input channel.

The DDC computer calculates the number of pulses which must be supplied to each stepping motor to effect the required change in the variable and stores these numbers in its memory. Each time a pulse is transmitted to a stepping motor, the number stored in the memory is counted down by one until it is zero (when the change desired in the variable is completed).

During each one-second sampling interval the computer continually scans the output channels, checking count-down words in the memory. If a word is non-zero, a pulse of the proper polarity is sent to the corresponding stepping motor and the count-down word decreased by one. The computer proceeds to the next channel doing the same operation and when all channels have been scanned, begins again with the first one. Assuming that the computer must be capable of driving any motor at its maximum speed, each output channel must be scanned approximately 150 times per second.

If the operator wishes to insert new set-points or controller settings or request certain output data, he signals the computer from the typewriter input. Such an input is of lower priority than the input scanner.

Besides supplying pulses for stepping motor type actuators, this DDC computer design is capable of supplying the other two required types of outputs.

Simulated at Texas City were those instruments at the left next to the air gages. Tests using an RW-300 computer proved DDC'd loops responded at least as well as conventional loops but in most cases both smoother and faster

A low-power motor can be used to rotate the wiper of a rheostat to provide a current for the current-to-pneumatic conversion needed to operate pneumatic actuators. The stepping motor provides the memory required for this analog output. The pulse-width type of output is obtained by replacing the stepping motor with a flip-flop. The flip-flop is set when a new Δm is calculated for the channel and is reset when the count-down word is zero. For a constant count-down rate the flip-flop is set for a time proportional to Δm.

Further research and development

From recent simulations and studies it appears that some form of Direct Digital Control for processes will, as one DDC manufacturer has stated, find a budding market in about two to three years. But, in order to make DDC completely practical (one computer manufacturer says this will be in a minimum of five years—Ed.), further development of input sensors (providing digital outputs economically) is necessary. Digital output devices must also be perfected with particular attention paid to speed of response, economics, and reliability.

The introduction of fluid logic with its low cost, low volume, and freedom from environmental limitations (which makes possible DDC computers which are not entirely electronic) will be a challenging factor.[7] The slower operating speed of fluid devices would limit the number of loops that could be controlled by a single machine to 10 or 15, but this would be compensated for by the decrease in cost. An increase in reliability would also be obtained by having 5 or 10 DDC computers, rather than one, controlling a large plant.

Since the cost of any computer is tied closely to the number of bits carried through calculations and the sampling rate, it may be desirable (strictly from a marketing viewpoint) to take advantage of the difference in quantization level required for transient versus steady-state operation.[8] That is, during an upset of the process, the level of quantization of the controlled and manipulated variables could be decreased and the sampling rate increased. The machine would be designed to control the process during transients or upsets using a given sampling rate and a low level of quantization (3 or 4 bits). When steady-state is approached and resolution of control becomes important, the sampling rate could be decreased and the level of quantization increased. In this way, it would not be necessary to build a computer capable of operating simultaneously at the maximum sampling rate with the maximum quantization levels, and this might result in significant reductions in computer cost.

Certain non-linear control algorithms could also be easily implemented by a DDC computer, which would be too expensive to add to analog controllers. For example, a bang-bang type of control (full-on or full-off) is often effective when errors are large. A combination of this type of non-linear control for large errors and conventional control (P-I) for small errors may result in distinctly improved control at no additional cost, since it involves only a minor modification of the DDC computer described.

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