Chapter 3

State-of-the-Art in Digital Control

The evolution of microprocessor technology—with the consequent availability of reliable, high-performance, low-cost digital hardware and powerful software tools, along with the growing difficulties in the maintenance of analog apparatus—has resulted in development of powerful digital control systems. The progress in microprocessor technology has led to continuously increasing performance in term of speed, computing power and functionality, through the integration on one chip of functions that in the past required many external components.

A similar evolution has taken place also in the software field: very powerful development environments have been carried out by specialized software houses and offered on the market. Such environments include a wide set of tools (debugger, software analyzer, profiler, I/O, graphic and mathematical libraries, etc.) for making the code development fast and easy, and for allowing its independence from the hardware. The availability of reliable hardware and software products together with their high performance and the associated low costs makes the use of the digital technology convenient and feasible for most power system controls. The benefits from the use of digital technology include:

- Greater flexibility and adaptability to different practical needs;
- Reduced number of subset types (electronic boards) to be used for the practical realization;
- Improvement in the user interface which becomes graphic, friendly and interactive;
- Enhanced control, alarm and protection functions;
- Sophisticated auto-diagnostics on-board;
- Easy and accurate setting and change of control parameter values, their constancy and independence from environmental conditions.

Moreover, the microprocessor technology makes easy the addition of new functionality such as:

- Adaptive or non-linear control;
- Data communication with the supervisory systems;
- On-line monitoring and the transient recording of meaningful control and process variables;
- Simulation of the unit under operation for a check of control parameter values without interfering with the plant.

Table 3-1 compares analog and digital control.

Table 3-1: Comparison between control types.

Item	**Analog control**	**Digital control**
Processing	Each operation is synthesized by a physical device (sums, integration, limitations, etc.). New functions require the addition of new hardware.	Functions are synthesized in software. No extra hardware is required for implementing new functions.
Model identification	Very expensive, causes machine unavailability. Accuracy depends on signal measuring quality	Direct translation of the digital control model from the studies and simulation platform.
Testing	Very expensive. Difficult execution. A lot of instrumentation and other facilities are required.	Many testing facilities can be made available, considerably reducing costs and risks. Data-acquisition automatically provides recording of many physical and internal variables; Software emulates instrumentation for different kinds of testing, such as step and sinusoidal signals, etc.;
Commission-ing	The need for a lot of instrumentation and numerous calibration tasks make the commissioning a quite strenuous and time-consuming job.	Commissioning can be carried on easily and in a shorter time because parameters are expressed in per unit or seconds, according to the mathematical model specified. A computer-based simulation station can be used for pre-commissioning and training. Adjustments can be automatically documented. Facilities such as recording, settings and readings make performance verification very easy.
Resolution	Theoretically infinite. In practice limited due to noise, drift, etc..	Limited to the converters and to the length of the word used to make the calculations. At the present time 16-bit A/D converters are used and, in some applications, 24-bit are available, to get maximum accuracy, although with a compromise for speed. Calculations are done in floating point, and with the available 80-bit co-processors, accuracy is practically unlimited..
Stability of Parameter values	Requires the use of very expensive components in every circuit board. Strongly affected by component aging. Thermal drift causes parameter limitations. Maintenance services produce parameter changes.	Digital implementation provides drift-free settings. Only analog interfaces need expensive and low drift components. Analog time constants used in these interfaces are of little importance to the process parameters. Parameters don't change because of maintenance services.
Interfaces	Done through conventional switches and instruments.	Interface design using human factors engineering concepts such as: familiar and standard nomenclature, engineering units, facilities for understanding and performing critical tasks; usability (dialogs, messages, acknowledgment, graphics).
Control Laws	Practically restricted to linear applications, with severe constraints for complex laws. Adaptive control laws are difficult to implement, requiring an excessive number of simplifications.	Complex control laws, such as adaptive control, can be easily implemented. Fuzzy controllers are equally feasible. Facilities to test and perform new ideas.

Item	Analog control	Digital control
Software	None	The real time core manages the execution of the various tasks. Software for off-line analysis are available.
Connectivity	The connection with the other plant devices is done through relays and analog signals.	Focus is held on serial interfaces - such as RS485 - with protocols such as ModBus. The growing use of Ethernet TCP/IP as field bus (suitable cables and connectors are being developed) allows direct and remote connection with the analyst even via Internet. Communication resources exist for remote control and integration with supervisory systems for purposes such as: remote settings changing, remote data logging, and customer protocols compatibility.
Self-diagnosis	None.	Wide self-diagnosis resources. New techniques are being developed based upon artificial intelligence concepts.
Costs	Stable and relatively low.	Decreasing. cost/benefit relationship may still be unfavorable in small size power plants.
Maintenance	Expensive due to the lack of self-diagnosis.	Can be considerably cheaper because of the use of the self-diagnosis. A trend towards not repairing printed circuit boards is being observed.
Bandwidth	Can be very large.	Still limited for extremely fast and complex loops because the Real Time Operating Systems need to keep switching between multiple tasks. For good performance, the times between the task switching and the latency for the interruptions must be smaller than the smallest control sampling rate. Use of assembly instructions to accelerate the process can bring serious maintenance problems.

This chapter examines the following topics:

- Section 1 reviews the fundamentals of digital control of dynamic systems.
- Section 2 describes the basic structure of a digital-control system.
- Section 3 describes application of digital control for a generator excitation system.
- Section 4 describes application of digital control for static var compensators.

3.1 Review of Digital Control of Dynamic Systems

Figure 3-1 shows a computer-controlled dynamic system.

The output from the process $y(t)$ is a continuous-time signal. The output is converted into digital form $\{y(t_k)\}$ by the analog-to-digital (A-D) converter. The conversion is done at the sampling times, t_k. The computer processes the measurements using an algorithm, and gives a new sequence of numbers $\{u(t_k)\}$. This sequence is converted to an analog signal by a digital-to-analog (D-A) converter. The real-time clock in the computer synchronizes the events.

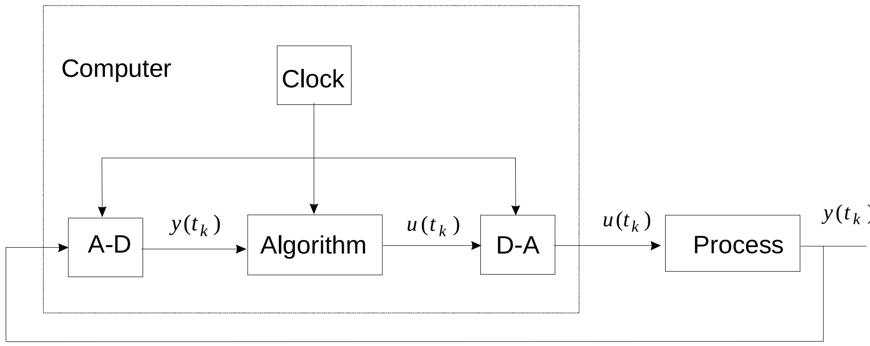


Fig. 3-1. Schematic diagram of a computer-controlled system.

3.1.1 Sampling of continuous-time signals

Assume that the continuous-time system is given in the following state-space form:

$$\dot{x}(t) = A\,x(t) + B\,u(t)$$
$$y(t) = C\,x(t) + D\,u(t)$$

The system has r inputs, p outputs, and is of order n. Normally a D-A converter is constructed so that it holds the analog signal constant until a new conversion is ordered. The relationship between the system variables at the sampling instants can be determined. Given the state at the sampling time t_k the state at the next sampling time t_{k+1} is thus given by:

$$x(t_{k+1}) = e^{A(t_{k+1}-t_k)}x(t_k) + \int_{t_k}^{t_{k+1}} e^{A(t_{k+1}-s')}Bu(s')ds'$$

The system equation of the sampled system is:

$$x(t_{k+1}) = \Phi(t_{k+1},\, t_k)x(t_k) + \Gamma(t_{k+1},\, t_k)u(t_k)$$
$$y(t_k) = C\,x(t_k) + D\,u(t_k)$$

where:

$$\Phi(t_{k+1},\, t_k) = e^{A(t_{k+1}-\, t_k)}$$

$$\Gamma(t_{k+1},\, t_k) = \int_0^{t_{k+1}-\, t_k} e^{As}ds\ B$$

Example 3-1. Consider the first order system:

$$\dot{x}(t) = \alpha\,x + \beta\,u$$

For periodic sampling with period τ ,

$$t_k = k\,\tau$$

Applying the formulas above we get:

$$\Phi = e^{\alpha\tau}$$

$$\Gamma = \int_0^{\tau} e^{\alpha s} ds\,\beta = \frac{\beta}{\alpha}\left(e^{\alpha\tau} - 1\right)$$

The samples system thus becomes:

$$x(k\tau + \tau) = e^{\alpha\tau} x(k\tau) + \frac{\beta}{\alpha}\left(e^{\alpha\tau} - 1\right) u(k\tau)$$

Pulse transfer operator. Use of the pulse-transfer operator allows the input-output relationship to be conveniently expressed as a rational function $y(k) = H(q)u(k)$ where:

$$H(q) = C(q\mathrm{I} - \Phi)^{-1}\Gamma + D$$

where q is a shift operator with

$$q\,x(k) = x(k+1)$$

Example 3-2. For a second-order single-input, single-output we have:

$$\begin{aligned} H(q) &= C(q\mathrm{I} - \Phi)^{-1}\Gamma + D \\ &= \frac{B(q)}{A(q)} \\ &= \frac{b_0 + b_1 q^{-1} + b_2 q^{-2}}{1 + a_1 q^{-1} + a_2 q^{-2}} \end{aligned}$$

This means that the input-output model can be written as:

$$y(k) + a_1 y(k-1) + a_2 y(k-2) = b_0 u(k) + b_1 u(k-1) + b_2 u(k-2)$$

Digital filtering. Digital filtering provides a great deal of flexibility, since the filter characteristic can easily be changed by tuning a few parameters. A digital filter has the general form:

$$y(k) = -a_1 y(k-1) - a_2 y(k-2) - ... - a_n y(k-n) + b_0 u(k) + b_1 u(k-1) + ... + b_m u(k-m)$$

where y is the filter output and u is the input measurement value. If all the a parameters are zero we will have a *moving average filter* with a finite impulse response. If some or all of a parameters are non-zero there is an *auto-regressive filter* which has an infinite impulse response. As a numerical example, a second order low-pass filter with a cutoff frequency of 300 Hz can be modeled by:

$$y(k) = -y(k-1) - 1.4752 y(k-2) + 0.0278 u(k) + 0.0557 u(k-1) + 0.0278 u(k-2)$$

Poles and zeros. The poles of a system are the zeros of the denominator of $H(q)$ or the eigenvalues of Φ. Because $\Phi = \exp(A\tau)$ it follows from the properties of matrix function that

$\lambda_i(\Phi) = e^{\lambda_i(A)\tau}$

The equation above gives the mapping from the continuous-time poles to the discrete-time poles. Through this analysis it's obvious that the left half of the s-plane is mapped into the unit disc of the z plane.

3.1.2 Dynamic performance

For real-time digital control, the criteria and algorithms for numerical integration of differential equations must result in numerical solutions close to the solutions of the corresponding continuous-time equations.

The basic point to be deeply considered is the altered dynamics of the system under control when moving from the theoretical description by continuous-time differential equations to the practical implementation where finite-differences algebraic equations (discrete-time dynamic system) are used [3-9].

This aspect is very important for real-time applications. Because of computing time constraints, it's not always possible to use complex numerical integration algorithms combined with very short integration step length (τ). Thus, the correspondence of digital control to the nominal analog performance must be verified.

In the following, the adequacy of several numerical integration methods are considered in terms of altered poles and residues of the related system transfer functions.

Computation of the altered dynamics. According to the above and the results shown in Appendix B, the critical factor affecting the dynamic behavior of digital control systems are the numerical integration method and the integration step length.

Analyzing the dynamic behavior of discrete systems it should be guaranteed that the "spurious modes" due to the integration algorithm are stable and timely convergent, and also that the variations $\Delta\lambda$, Δc of initial eigenvalues λ and of the related residue c are negligible. The value of the integration step τ strongly affects the highest poles of the discrete-time system: the lower the value, the better the discrete time system approaches the corresponding continuous model, but the higher the digital hardware performance requirement. For small variation (sensitivity method) of original generic pole ($\Delta\lambda/\Delta \ll 1$), the following relations allow evaluation of the corresponding altered dynamics:

$$\frac{\Delta\lambda}{\lambda} \cong Q(r) - 1$$

where

$$r = \lambda\tau$$

$Q(s\tau)/s$:

is the "equivalent integrator" of the numerical integration method (see Appendix B).

$$\frac{\Delta c}{c} \cong \frac{\Delta\lambda}{\lambda} + r\frac{dQ(r)}{r}$$

In case of Explicit Euler (EE) integration method:

$$Q(r) = \frac{r}{(e^r - 1)}$$

An exact calculation of the dynamic performance modification is possible for single step integration methods. In fact, coming back to the first order linear differential equation:

$$\frac{dx(t)}{dt} = f[x(t); u(t)] = \lambda\, x(t) + u(t)$$

that allows a complete and correct analysis of a given mode (λ) of a linear "diagonal" dynamic system (see also the conclusion of the first section of Appendix B), the solution of this equation can be expressed as the sum of a particular integral $I(t)$, selected according to $u(t)$ and a term proportional to $e^{\lambda t}$:

$x(t)=ae^{\lambda t} + I(t)$, (*a* being a suitable constant).

By applying a single-step integration method, the differential equation becomes a finite-difference equations of type:

$$x_{K+1} = \rho(\tau, \lambda) x_k + \alpha_k$$

where $\rho(\tau,\lambda)$ is a function whose structure depends on the integration method, and α_k is, in the most general case, a linear combination of the input $u(t)$ and its derivatives, calculated at instant t_k and t_{k+1} (and possibly at instants between t_k and t_{k+1}).

The theory of linear finite-difference equations shows the solution of the above equation to be sum of a "particular integral" I_k , selected knowing the following values of α_k and a term proportional to ρ^k, where ρ is the root of the characteristic polynomial associated to the difference equation:

$x_k = a\rho^k + \hat{I}_k$ (*a* being a suitable constant)

The x_k values can be considered as the values, calculated for $t=t_k=k\tau$, i.e. sample-values, of a continuous-time function $\hat{x}(t)$ given by:

$$\hat{x}(t) = \hat{a} e^{\hat{\lambda} t} + \hat{I}(t)$$

assuming

$$\hat{\lambda} = \frac{1}{\tau}\ln\rho$$

$$\hat{I}(k\tau) = \hat{I}_k$$

We can see that the solution of the discrete system is formally similar to that of the continuous system. In particular, it's evident that $\hat{\lambda}$ affects the solution of the discrete system like λ affects the solution of the continuous system.

$\hat{\lambda}$ can therefore be taken as the eigenvalue of the discrete system and can be compared with the corresponding eigenvalue of the continuous system.

In this regard, let $\hat{\lambda} = \lambda + \Delta\lambda$; thus we have:

$$\frac{\Delta\lambda}{\lambda} = \frac{\ln[\rho(r)]}{r} - 1$$

This equation highlights the exact transformation that, depending on the specific single-step integration method, links the continuous system eigenvalue to the discrete system eigenvalue.

Table 3-2 shows the results obtained for different integration algorithms. As an example, with EE method and τ = 10 ms (integration step), the change of a 20 ms continuous model time constant is: $\Delta\lambda = \lambda/4$. Then, the resulting modified time constant of the corresponding discrete model is 15 ms, instead of 20 ms.

The table also shows, considering an oscillating system (imaginary eigenvalues), that the EE integration algorithm results in instability.

3.2 Basic Structure of a Digital Control Systems

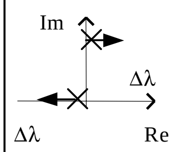
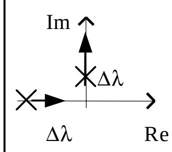
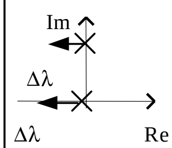
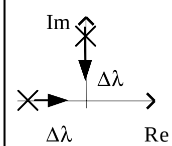
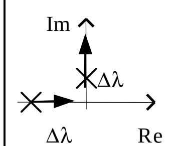
The general structure of a process computer interacting with a physical process consists of the following parts:

- central data processing unit
- process communication channels
- A/D and D/A converters
- sensors and actuators
- physical process.

Figure 3-2 shows the basic structure of a control system:

The physical process is observed with sensors. Conversely, the process is influenced through actuators. A digital control system works only on information in numerical form, therefore the collected electrical variables have to be converted via analog to digital (A/D) converters. Information from different source points distributed in space is brought to the central unit via communication channels. The central control unit interprets all incoming data from the physical process, sends control signals, take decisions on the basis of the program instructions, exchanges data with the human operators and accepts their commands.

Table 3-2: Altered dynamics due to numerical integration method.

Integration Method	Δλ/λ	Δλ	Pole Shift
EE	$-\frac{1}{2}\tau\lambda + ...$	$-\frac{1}{2}\tau\lambda^2 + ...$	
EUTRAP	$-\frac{1}{6}(\tau\lambda)^2 + ...$	$-\frac{1}{6}\tau^2\lambda^3 + ...$	
Runge-Kutta 3	$-\frac{1}{24}(\tau\lambda)^3 + ...$	$-\frac{1}{24}\tau^3\lambda^4 + ...$	
Runge-Kutta 4	$-\frac{1}{120}(\tau\lambda)^4 + ..$	$-\frac{1}{120}\tau^4\lambda^5 + ...$	
EXTRA	$-\frac{5}{12}(\tau\lambda)^2 + ...$	$-\frac{5}{12}\tau^2\lambda^3 + ...$	

Computer structures. A computer system is normally built around a *central processing unit* (CPU) to which are connected *peripheral units* performing different functions: keyboard, video interface, disk driver, input/output (I/O) cards. Figure 3-3 shows the conventional organization of a computer system. In this configuration, the peripheral units may communicate directly only with the CPU and only one peripheral unit at the time may be active exchanging data.

The CPU-centered configuration is inherently inefficient because all data has to pass through the CPU, even if the CPU does not need it. It’s more effective to design a computer system where the peripheral units are more independent and have added computing capacity. The peripheral units are connected together with a bus by which each unit can communicate with all the others. Figure 3-4 shows the principle of a bus-organized computer system.

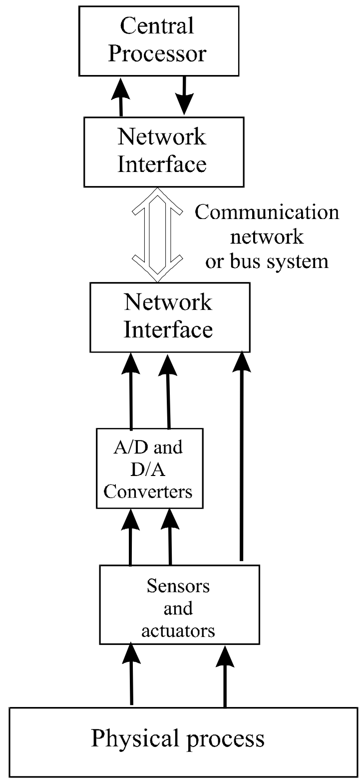


Fig. 3-2. The basic structure of a digital-control system

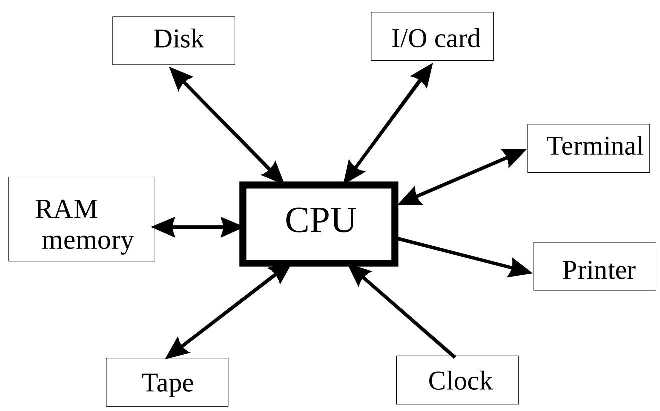


Fig. 3-3. The conventional organization of computer systems.

In the next two sections we examine two applications of digital control in power systems.

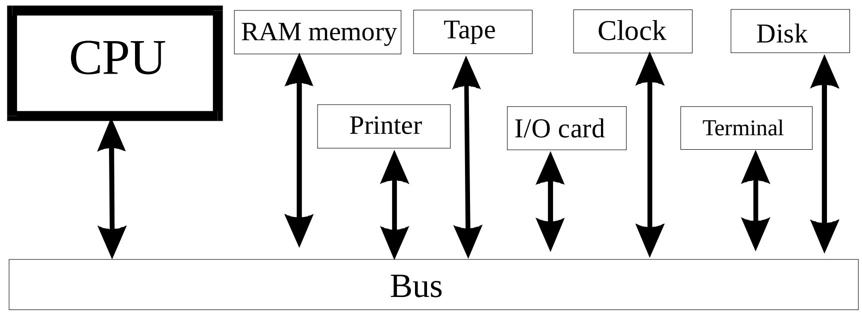


Fig. 3-4. Principle of bus organization.

3.3 Evolution of Excitation Control Systems through Microprocessor Technology

The general scheme of a modern static excitation system is shown in Figure 3-5. It consists of two parts, respectively named *control unit* and *power unit.*

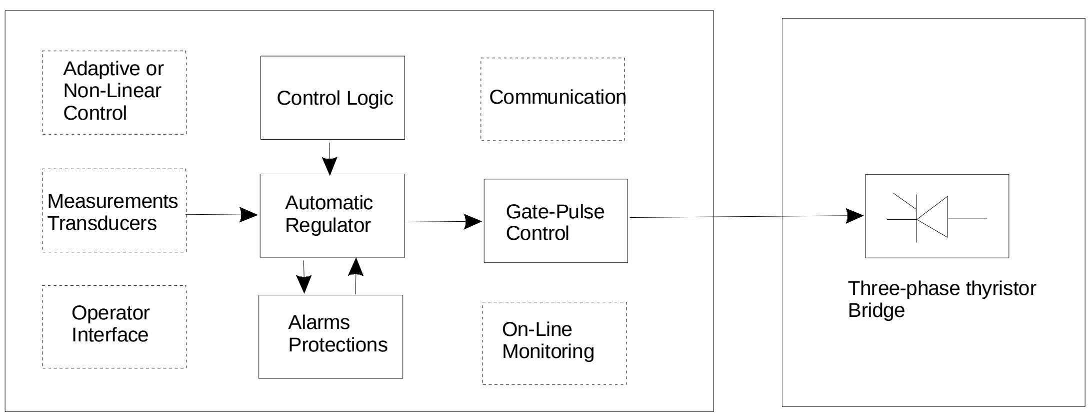


Fig. 3-5. Principle scheme of a modern static excitation system.

In the control unit the blocks marked with solid lines represent the conventional functions such as measurement of process quantities, control logic, automatic regulation, alarms and protection, and phase control of firing pulse. The blocks with dashed line show the additional functions that can be introduced using a digital control system. The power unit supplies the excitation current to the field winding of the generator and mainly consists of a three-phase full-controlled thyristor bridge.

In the following a short description of the characteristics and performances of the conventional analog control unit is given, as reference for the requirement specification and the correct design of a digital one. Referring to Figure 3-5:

- The first block on the left includes circuits for measurement and computation of the following process quantities: active and reactive power, electrical machine voltage and flux, HV bus voltage, excitation voltage and current, generator frequency or speed. The major part of these measurements requires high resolution (about 12 bit for digital transducers) and fast response (response time less than 20 ms).

- The second block *Automatic Regulator* consists of several control loops. The main loop regulates the stator voltage and has additional feedback for improving the electromechanical stability (power system stabilizers, PSS) and for compensating the reactive power drop (compounding). Auxiliary loops limit the working point of generator in over/under excitation and the maximum stator flux. A further possible auxiliary loop, overlapping the previous, regulates the machine reactive power. The main loop requires a bandwidth of 5–10 radians/second.
- The block on the right controls the phase of thyristor firing pulses. It maintains the firing angle inside the allowed range, compensates the gain variations (depending on supply voltage) and makes the bridge transfer characteristic linear.
- The remaining two marked blocks represent the control and the protection logic. They manage the different operating modes of AVR, detect fault or incorrect operating conditions, and provide proper alarm signals in order to improve the safety and the reliability of the system.

Passing from the analog to the microprocessor technology, the most critical problems, requiring particular care in the design phase are:

- The accuracy, resolution and time response of measurement, transducers, and thyristor firing pulse phase modulation;
- The dynamic performance of control loops taking into account the altered dynamics from the sample and hold of the I/O signals;
- The reliability and availability of the practical realizations.

3.3.1 Hardware architecture

The hardware configuration of the newest digital AVRs with decentralized architecture consists of a central system and of modular terminal boards which are placed close to the measurement points. The central system (see Figure 3-6) mainly consists of CPU and A/D-D/A conversion boards, which communicate via a local bus. It performs measuring, filtering, regulation, logic and communication tasks as well as sampling and holding of the measurements and control variables requiring fast management. Less critical data are managed by the modular terminal boards which achieve a distributed I/O. These peripheral boards communicate with the central system by a field bus.

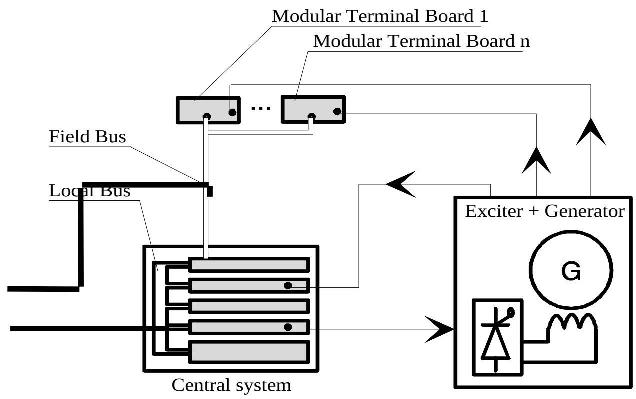


Fig. 3-6. AVR typical hardware architecture.

3.3.2 Software organization and development environment

The AVR software, executed by the central system CPU boards, implements measuring-filtering, regulation, logic, firing, monitoring and communication functions. The software is normally organized in tasks, characterized by different execution frequencies, in order to optimize the hardware resources and achieve the required dynamic performances. For example filtering functions have high execution frequency to avoid possible altered dynamics of the fast control loops, whereas the communication with the human-machine interface can be executed with lower priority without decreasing the overall performance. To manage the CPU time and the task execution, "ad hoc" schedulers, real-time kernels or operating systems can be adopted. They give the CPU control to the tasks with the right frequency according to priority level. "Ad hoc" schedulers usually lead to optimized, but quite rigid solutions; a few software changes can require a new plan of the scheduler. Operating systems are more flexible, allowing a plain and structured solution. They can also manage complex resources, for example drivers and protocols for the communication with Local Area Networks (LAN).

Another advantage of operating systems is portability, while the disadvantage is the non-optimized use of resources and therefore the requirement of more powerful digital hardware. Real-time kernels are an intermediate solution; in spite of lower use of CPU resources they are able to supply useful primitives to organize the software execution.

Similar considerations characterize the software organization: low-level programming languages lead to optimized solutions, whereas high-level programming languages and structured programs lead to plain solutions. General purpose real-time development environments are present on the market today, providing useful tools to write, to compile and to test the software. Some are PC-based. They permit remote debugging by downloading the machine code to the CPU boards memory and by monitoring the execution as normal debuggers, showing the high or low level code processing.

3.3.3 Reliability and safety

Care in the hardware choice concerns the possible reliability improvement for embedded real-time systems. Digital hardware able to run code resident on EPROM or flash-EPROM and to store operative parameters on EEPROM is employed. Watchdog circuits are usually required on the boards to detect CPU crash and other fatal conditions. The software can also improve the reliability. It verifies the measurement coherence, filters the digital inputs and monitors the correct work of peripherals. Other precautions, for example cyclic redundancy checks and check-sums, are used to control and to recover data errors. Diversified AVR configurations are used for different plant sizes. The AVRs of the largest generators have two and sometimes three central controls. The most popular redundancy configuration is two identical channels: one is active while the other is standby, waiting to become active if the first malfunctions.

3.3.4 Operator interface

A friendly and effective operator interface can easily be implemented. It allows both easy and accurate setting of customized data and regulation parameters, and of the on-line display of the most important process variables. Different Human-Machine Interfaces (HMI) are possible, going from a simple LCD display and dedicated push-button to a colored graphical monitor with standard or dedicated keyboard up to a portable PC. Data exchange with the control room supervisory system is possible through a LAN.

3.4 Application of Digital Control to SVCs

As an example from one manufacturer, Figure 3-7 shows an overview of the ABB MACH 2 computer structure and indicates how the control system interfaces with the high voltage components of a SVC.

3.4.1 Control and protection design

The control and protection system provides the following features:

- control functions
- valve control
- protection
- alarms
- operator interface (locally and remotely)
- transient fault recorder
- internal supervision
- remote interrogation

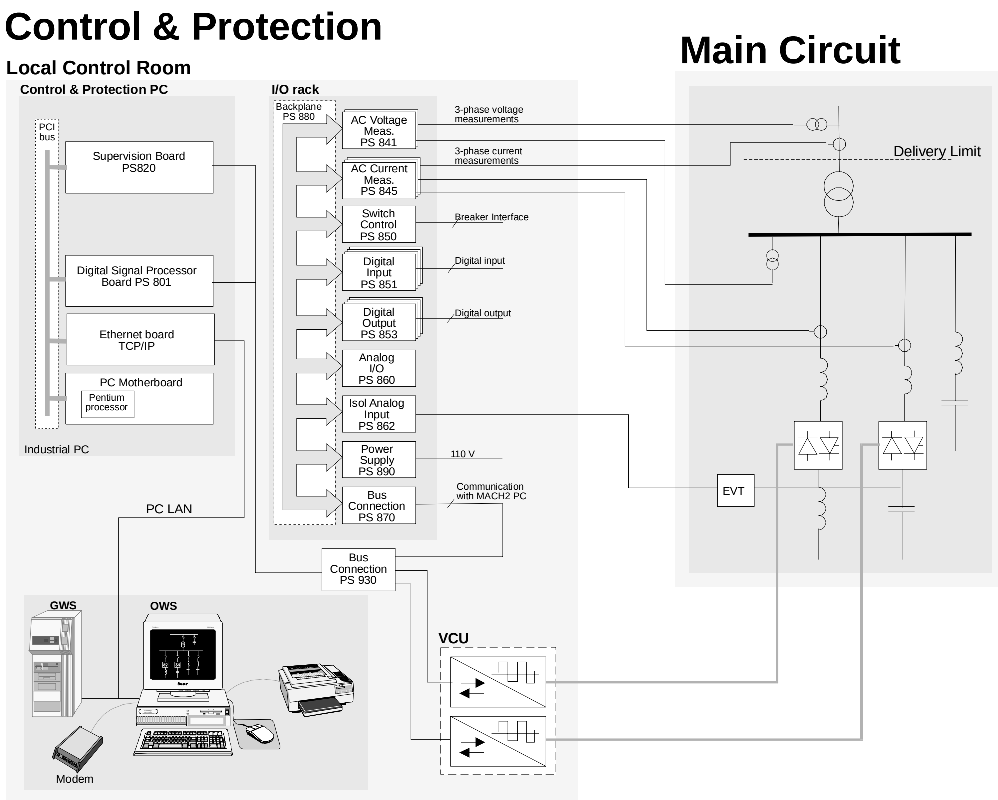


Fig. 3-7. MACH 2 computer structure.

All functions within the control and protection system are realized with the MACH 2 building blocks, consisting of a main computer and an I/O system. High speed applications, e.g., fast regulators, firing control etc. are realized in DSPs, while less demanding functions, such as operators interface, are realized in the main computer CPU.

The I/O rack serves as an intelligent interface between the main computer and the high voltage side equipment. It contains digital and analog I/O boards, and also a DSP board, PS860. The communication between the main computer and the I/O is by field busses.

3.4.2 Communication

Local Area Networks (LANs) are used to connect together several locations (called nodes) so that they can all communicate with each other. The LAN used is the well-known IEEE 802.3 (Ethernet). This bus uses the well-proven Carrier Sense Multiple Access with Collision Detection (CSMA/CD) principle to arbitrate access to the bus. Transmission speed is normally 100 Mbit/s. This bus can transfer data using many different protocols (even at the same time), e.g., TCP/IP.

In designing a new and modern control equipment, it’s necessary to use field busses. The two field bus types that are used are CAN and TDM.

The CAN bus is used for communication in both directions between the main computer and digital I/O circuit boards. The transfer speed of a CAN bus is less than that of a TDM bus.

The TDM bus is single direction and used for high-speed measurement signals. The TDM bus operation status is continuously monitored by the receiving nodes in the control and protection system, and detected faults will give alarm.

3.4.3 Internal supervision

Periodic maintenance is minimized by the extensive use of self supervision built into all microprocessor-based electronic units, and by the possibility to check all measured values during operation without disturbing the operation.

The internal supervision of microprocessor-based systems includes auxiliary power supervision, program execution supervision (stall alarm), memory test (both program and data memory) and supervision of the I/O system communication over the field busses. The operation of the field busses is monitored by a supervisory function in the control and protection system that continuously writes and reads to/from each individual node of the system.

Another example of integrated self-supervision is the switch control unit. In this unit the outputs to the breakers are continuously monitored to detect failure of the output circuits of the board.

3.4.4 Automatic voltage control

The automatic voltage control consists of a closed-loop voltage regulator formed by a positive sequence voltage response, a PI-regulator with variable gain, and the control rule generator. The voltage reference signal from the HMI is transformed into a reference for the voltage regulator. The reference range is limited by parameters and indicated on the HMI for operator feedback. Feedback for the voltage control is the primary voltage, which is measured from the high voltage bus. The regulator output is a susceptance reference value further distributed as an input to the control pulse generator.

3.4.5 Gain supervisor

The control system provides a gain supervisor function for supervision of the SVC MVAr output. Upon large changes of the impedance in the connecting network the SVC reactive power output may start to oscillate. This can be explained by high preset regulator gain versus new power system impedance. For oscillations detected in the susceptance reference, B_{ref} , the gain supervisor will automatically reduce the voltage regulator gain until the SVC output becomes stable again. When this occurs an alarm will be given and the gain can manually be reset to normal value from the HMI.

3.4.6 System voltage measurement

The main objective of the data acquisition unit, DAU, is to measure the voltage response on the primary side of the main transformer. The voltage response, which is fed to the voltage regulator, is processed in the DAU in order to meet the dynamic demands regarding speed and stability.

If a TCR is operated with symmetrical firing, the true voltage response fed to the closed control loop should not contain negative sequence components or harmonics other than fundamental. On the other hand, if the task is to control unsymmetries, the TCR must have different controllers for positive and negative sequence voltage components. Therefore an α/β-transformation is employed in order to transform the three-phase voltage into a rotating vector system in the alpha/beta plane, a so-called space vector representation (see Appendix C). The voltage space vector is thereafter fed to a function that can extract both the positive and negative sequence components from the voltage space vector.

3.4.7 Control pulse generator

The main objective of the Control Pulse Generator, CPG, is to generate control pulses for further distribution to the Valve Control Unit, VCU. The most important input quantities are the susceptance reference from the voltage regulator and the measured SVC-bus voltage. The susceptance reference serves as the control reference value from the voltage regulator while the SVC bus voltage is used for synchronization of triggering pulses and simulation of TCR and TSC current.

The other control functions are as follows:

- power oscillation damper
- control of external devices
- loss minimization functions
- TCR direct current control
- sequence control of breakers
- protective control functions
- undervoltage control strategy
- supervision of faults in the thyristor triggering system

3.4.8 Operators interface

The operator interfaces are provided by workstations for local and remote control (Figure 3-8). These are typically Windows NT computers interfaced to the main computer via the local area network, LAN.

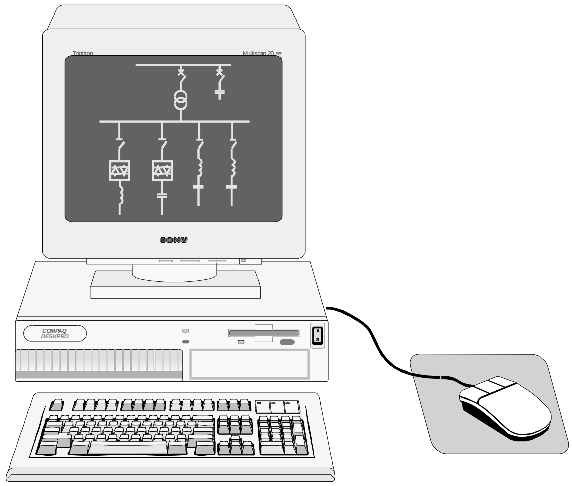


Fig. 3-8. Operator work station.

The main functions are:

- Full graphic status displays of various views.
- Display and adjustment of protection settings and control parameters.
- Alarms—all events classified as alarms in order of severity.
- Fault list—all persistent alarms in chronological order.
- Sequence of events—all events/alarms including logging of orders.

The operator interface may also provide high performance transient fault recording.

3.4.9 Remote interrogation

Remote interrogation of the control system may be provided by modem communication. An on-line graphical debugger allows the user to view several graphical programming tool drawings at the same time and inspect any internal software “signal” in real time by just double-clicking on the line that represents the signal. This fact makes the graphical debugger a very useful not only for monitoring, but also for maintenance and debugging. The graphical debugger also allows all thresholds, setpoints, and timer settings to be easily displayed in various formats (e.g., as tables).

3.4.10 Valve control

The Valve Control Unit (VCU) is the electrical/optical interface between the firing control system and the thyristor valves. The VCU is realized by two special boards giving a compact design.

3.4.11 Application software development

The application software for the MACH 2 control and protection system are produced using a fully graphical code generating tool called HiDraw. It is Windows-based software that is very easy to use as it is based on the easiest possible select, drag, place method. It's designed to produce code either in a high level language (PL/M or ANSI standard C) or in assembly language. For functions not available in a comprehensive library (one for each type of processor board) it's very easy to design a new block and link to the schematic with a simple name reference.

A schematic drawn in HiDraw consists of a number of pages. One page specifies cycle times and execution order of the other pages. HiDraw includes an on-screen reasonability check of the drawn schematic, and automatic cross reference between the pages. As output, it produces code and a "make" file ready to be processed.

The next step in the workflow is to run the make file (on the same computer) which means invocation of the necessary compiler/assembler and link locate programs (usually obtained from the chip manufacturers). The result is a file that is ready to be downloaded from the computer to the target, and stored in the flash PROMs.

3.4.12 Debugging facilities

For debugging, a fully graphical debugger operating under Windows is used. The debugger allows the operator to view several HiDraw pages at the same time, and look at any internal software "signal" in real time by just double clicking on the line that represents the signal. Parameters can easily be changed by double clicking on their value. As a complement, a fully symbolic debugger is available either on a computer or a dumb terminal.

For fault tracking, it's easy to follow a signal through several pages because when a signal passes from one page to another, a double click on the page reference will automatically open the new page and allow the trace to continue immediately on the new page. There are also a number of supporting functions such as single or multiple stepping of tasks (one page is normally a task) and coordinated sampling of signals.

The fact that the debugger allows inspection of signals while the application is running makes it very useful not only for debugging but also facilitates maintenance. Because the debugger works in the Windows environment, it's also possible to transfer sets of signal values to other Windows-compatible programs, such as Excel, for further analysis.

3.5 Trends in Digital Control

Electronics have evolved at an astounding rate in the last years. It's very difficult to make long-term predictions, although trends are apparent. Basically it can be said that:

- Availability of resources from digital controllers will shorten the time between the development of a new control law and its practical implementation.
- The improvement in speed and reliability of the communication channels will allow the creation of safe methods for remote commissioning and maintenance.

- The adoption of common use, more flexible hardware and software is an observed trend, making systems integration much easier and lowering maintenance costs because of high scale production.
- An easy access to a superior hierarchical level can be provided by object-oriented technologies. For instance, the use of OPC (Object Linking and Embedding for Process Control), where the controller opens a window in a higher level supervisory system, and makes available all of its resources (adjustments and commands) without the system integrator worrying about the knowledge of the controller implementation details.
- On-site implementing upgrades should be easier, because no hardware changes will be needed. On the other hand, design and documentation efforts demanded by software modification could be large.
- PC-based systems are becoming more cost-effective, and have been occupying traditional PLC space.
- The costs will drop, as a result of the electronic circuit large scale integration increase, as well as new technologies and the enhancement of software techniques.
- There will be a need to develop more system analysis tools to handle the large diversity of control laws performing in different machines of the system.

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