

MICROPROCESSOR SYSTEMS AND ARCHITECTURES FOR APPLICATIONS TO THE CONTROL AND PROTECTION
OF ELECTRIC POWER SYSTEMS

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Abstract:

Some design concepts for microprocessor applications to the control and protection of electric power systems are presented. A formal design methodology is outlined. Present microprocessor applications to the control and protection of the electric power generation, transmission and distribution systems are summarized. These applications are generalized to provide a basis for identifying a set of "standardized application modules." A projection is made of probable future developments in microprocessor applications to the electric power industry. A probable development is believed to be the use of hierarchically structured networks of microprocessors to provide, through distributed processing, more cost-effective and reliable control and protection than is possible through centralized processing.

I. INTRODUCTION:

The digital computer has been used for solving a large range of problems in the electric power industry since computers became commercially available in the late fifties. In the beginning the applications were largely limited to the design and analysis of electrical machinery and electric power networks. As minicomputers with the capability of operating in real-time modes became available, this new technology was applied to a variety of control and data logging applications. Research began in the late sixties on the application of digital computers as a possible replacement for the relays then used to detect and locate faults on electric power system networks.

The development of low cost, but powerful microcomputer systems provided an important element needed for the cost-effective implementation of computer control and protection of electric power systems. It is expected that microcomputer-based systems for the control of electric power systems will improve the reliability, the availability, and security of service while also increasing the system operations' simplicity and providing more flexibility in responding to new demands. Some new design procedures and concepts are of assistance in adapting this new technology in effective ways to meet the functional requirements in the decade ahead. The latest developments in distributed processing computer networks, as well as new techniques in the design of decentralized control systems, are expected to strongly influence the control and protection of

electric power systems.

It is the purpose of this paper to identify and describe some of the new design concepts. A necessary preliminary step is to summarize the state of the art in the application of microcomputers to the control and protection of electric power systems. While some brief reports [1,2] have been published on these microprocessor applications, the comparison and analysis has not previously been presented in this fashion. The applications described in the overview are then analyzed to determine the basic systems and architectures used. This analysis leads to the identification of the need for new implementations of protection and control functions which would more fully and effectively utilize the capabilities inherent in microcomputer-based systems. A Distributed Processing Microprocessor-Based Hierarchically-Structured (DPMH) system has been proposed [14,15] and is briefly discussed as an example of some of the new design concepts.

Part two of this paper discusses general control system design methodology. Existing and future control functions are described. Part three presents the overview of microcomputer applications with an emphasis on the relations between system architectures and the processor tasks to be performed. Part four generalizes the computer architectures and the protection and control functions. Part five outlines some possible new design concepts and procedures.

II. DESIGN METHODOLOGY:

It is useful to consider a formal methodology which insures a detailed and appropriate design. An example of one such process is illustrated in Fig. 1. The proposed approach is concerned primarily with decomposing systems and then reassembling them. The process of decomposing is important because new possibilities for implementing existing functions as well as possible new functions may be revealed. Thus we now consider some characteristic decomposition procedures:

Hierarchical structural decomposition is useful to distinguish between power plants, transmission substations, and distribution systems at level 0. Successively higher levels of control are to be found at levels 1 through 4 as follows: utility-wide operational control centers are at level 1; power pool operations centers at level 2; regional and national coordinating centers are located at

levels 3 and 4, respectively.

Hierarchical functional decomposition is useful in identifying functional groupings such as:

- Energy Control Center:
 - *automatic generation control (AGC)
 - *economic dispatch calculations (EDC)
 - *supervisory control and data acquisition (SCADA)
 - *automatic voltage/var control (AVC)
 - *security monitoring (SM)
 - *security analysis (SA)
- Power Plant:
 - *monitoring and control of prime movers
 - *monitoring and control of generators
 - *other supervisory functions
- Transmission Substations:
 - *data logging, recording, acquisition
 - *power apparatus protection
 - *local control functions
- General Functions at any level:
 - *communications
 - *improved man-machine interfaces

Time decomposition can be illustrated by the following examples:

*protective relaying	hundreds of microseconds
*speed governors	hundreds of milliseconds
*load frequency control	seconds
*economic dispatch	minutes
*unit commitment	hours
*load forecasting	days

Decomposition by objectives includes at least the following: regulation, optimization, and stabilization.

Modes of operation decomposition usually defines normal, preventive, emergency, and restorative modes of operation.

Decomposition of control tasks consists of directing control, optimal control and adaptive control.

From the decomposition procedures performed it is evident that there could be established several structure-goal relations for each of the decomposition processes. Assembling procedures can be performed and the identification process is accomplished. Algorithms and models can be developed and analysis performed to define parameters and functions.

It is important to note that the analysis process is a critical methodological step because new possibilities for microcomputer applications are suggested by careful analysis. A limitation of much of the design to date is the one-for-one functional replacement of present devices by microprocessor-based units which perform precisely the same function. This approach is reasonable to allow for the upgrading of existing control and protection systems. However, many new approaches may be ruled out by such a conceptual constraint on the design. The next section summarizes the important applications of microprocessor-based devices in the control and protection of electric power systems. These applications are selected to illustrate some of the trade-offs between the direct implementation of existing functions versus the synthesis of conceptually new functions.

III. MICROPROCESSOR APPLICATIONS:

Several microprocessor-based systems are discussed in this section. The scope of the applications range from limited, very specific control task subsystems up to integrated control and protection systems. Each application is considered in the following contexts: function performed, system architecture, and system type (process controller, I/O controller, communications controller, signal processor).

III-1. Power Plant Applications

Hydropower Generation Control:

A hydro-electric power generation controller [3] utilizes microcomputers to perform the following control functions:

- *operation of solenoids and contactors
- *adjustment of voltage set point for voltage regulator
- *automatic synchronization of generator units
- *adjustment of governor set point

The overall task of this system is to control the water turbine-generator unit from start up, through all operating regimes, to the shut down of the system when the unit is not needed on line. The microprocessor used for this application is a 12-bit word size, model TLCS-12 manufactured by Toshiba (Japan). The speed of operation is increased and the convenience of programming enhanced by microprogramming features included in the design of the microprocessor. Two processors are used in this system with provision for self-initialization and self-diagnosis of failures. It is designed as a distributed system with the several modules interconnected using a daisy-chained bus.

Gas Turbine Generator Control:

A microprocessor-based control system has been implemented for gas turbine-driven generator units [4]. This system has been designed to interface to the generating station load control center. The control unit is modular in design for ease of maintenance and also for flexibility in adapting to future requirements. The modules are microcomputer, memory, and six basic function boards. These six boards handle the analog input/output, the digital input/output, communications, and display functions. The microprocessor used is a Motorola 6800. The control program is stored in a Programmable Read Only Memory, PROM. Microprocessors are used in two basic system configurations. In one configuration, a microprocessor is used to handle data communications between the GE4010 at the Energy Control Center and an Interdata 7/16 minicomputer at the operator office. The other configuration utilizes a microprocessor to interface sensors and controls on a gas turbine unit to the Interdata minicomputer and an operator display board.

Microprocessor-Based Synchronizing:

A microprocessor-assisted synchronizing system has been developed to aid operators in placing a generator on the bus [5]. The machine voltage and frequency are compared with those of the station bus and prompts provided to the operator to

alter either the excitation or speed as needed to attain synchronization. The microcomputer provides the signal to the circuit breaker which connects the generator to the bus when the amplitude and phase are appropriate. The microprocessor used in this application is a National SC/MP chip which has an 8-bit word length. The operating program is again stored in Read Only Memory, ROM. A fully automatic controller is contemplated as an extension of the present system. Such logical extension would require that the prime mover governor and the exciter for the generator be placed under control of the microprocessor.

III-2. Transmission Substation and Distribution System Applications

Alarm Logging:

Alarm logging is a very appropriate application for microcomputers in electric substations. A system designed to directly substitute for existing annunciator systems is available [6]. This system also provides an event recording feature. The modularity of the system provides the applications engineer with a great amount of flexibility in tailoring a system to the particular needs of the installation. Another product [1] is a Sequence of Events Recorder, SER, which can be tailored to a wide variety of event recording requirements for electric substation monitoring. This system provides for control of both the data acquisition functions and for the storage of the data for later retrieval and processing. The operating software for the microprocessor is stored in PROM.

Transformer Tap-changing:

Control of tap-changing for substation transformers is described in two references [7,8]. The tap-changing is controlled to regulate the voltage on the outgoing lines from the substation. A microcomputer system monitors the outgoing bus voltages and compares the values to the present "set values." When the difference is above a specified threshold, the computer issues control commands to change the taps appropriately. The microprocessors used are 8-bit machines with program stored in PROM. One of the systems uses the Intel 8008 processor [7].

Revenue Metering:

There has been only one microprocessor-based algorithm proposed [9] for revenue metering. The necessary voltages and currents are digitized and correlations between voltage and current calculated by orthogonal functions to yield the real power, P , and the reactive power, Q . This algorithm is particularly well-suited for microprocessor implementation because only very simple arithmetic operations are involved. The use of 8-bit microprocessors is proposed for this signal processing task.

Digital Relaying:

Research on the development of digital relaying began in the late sixties. The term relaying in the context of electric power systems refers to the measurement of voltages and currents in electrical equipment or power lines with the objective of determining when and where a fault occurs. Much

work has been carried out and reported in the intervening decade [10]. However, relatively few papers or reports document the application of microprocessors in this application. Digital relaying is predicated upon digital processing of the digitized current and voltages. A fault on the power line or in the equipment causes distortion in the current and voltage waveforms which enables the detection of the occurrence of a fault. A wide variety of algorithms have been implemented for this signal processing. The basis for these algorithms ranges across: Fourier analysis, digital filtering, numerical solution of differential equations, and transient analysis. The results of the signal processing can be applied to the protection of: transformers, transmission lines, distribution lines, and generators. Microprocessors utilized to date have generally had 8-bit words. The recent development and production of 16-bit size machines provides an opportunity to investigate the possible advantages of longer word length in this signal processing.

Integrated Transmission Substation Systems:

The idea of developing an integrated control and protection system for applications to electric transmission substations is relatively new and is the subject of on-going research. The several systems developed in the past excluded the protection functions and were designed around minicomputers. The requirements for such an integrated control and protection system are well described in the RFP 5289 issued by the Electric Power Research Institute, EPRI. A research project, RP 1359, has been negotiated with several research institutions and manufacturers. This system is to integrate the following: automatic control of equipment, protective relaying, revenue metering, data logging, and fault recording. Interfaces will be provided to both conventional signal transducers and to new transducers being developed concurrently. The system can be connected to other existing equipment in the substation such as Supervisory Control and Data Acquisition, SCADA, systems. A well-designed man/machine interface is to be provided for the operators. The architecture being considered is a multiprocessor system using microcomputers. Two basic approaches are being considered: centralized and distributed. Several distributed systems are under consideration. Microprogrammable microprocessors will probably be used to provide greater flexibility in the system design while using "standardized" hardware for ease of maintenance. It is also expected that the I/O controllers and the communications interfaces will be microprogrammable for the same reason. The requirements for real-time operation, decisions made in milliseconds, and the imperative for reliable operation can be adequately met by the microprocessor-based, distributed processing system.

Integrated Control and Protection for Distribution Substations and Systems:

The automatic control and protection of distribution substations has steadily advanced over time to a present level of complexity and sophistication which appears to exploit to the maximum possible extent the technology of electromechanical and analog devices. The development of digital technology for the control and protection of the

distribution substation has just begun. The systems thus far developed perform only a limited number of functions. A representative sample of desired functions is given in the recent EPRI RFP 5461 titled, "Integrated Control and Protection of Distribution Substations and Systems." Functions described include: data acquisition and logging, control of equipment, protection of equipment, status monitoring, and interfaces to related systems. The system is to be microprocessor-based and modular in design. Future research projects will explore possibilities for overall distribution automation. Also being studied at the present time are the technologies for communication requirements for distribution automation. The types of communications technology considered are: power line carrier, telephone lines, and point-to-point microwave radio systems. The expanded need for communications to support greater levels of automation and improved control may dictate different choices of communications over large geographic areas. It is expected that microprocessors will be applied in the communications area to not only provide adequate monitoring of the operation of the data communications, but also to increase the reliability and security of the data communications systems.

III-3. Supervisory Control and Data Acquisition (SCADA) Systems

There are a variety of different data acquisition and control systems available today. Most of these systems are classified as SCADA systems, but there is no existing standard which defines the functional performance or the structure of these systems. Thus SCADA systems may range from very simple data acquisition systems at one extreme to very sophisticated control and monitoring systems at the other extreme. These systems also vary widely in size from systems with several hundred RTU's. Some systems are stand-alone, independent units while others are connected to energy control systems. SCADA systems are applicable in all parts of the electric power system: generation, transmission, and distribution.

There are two general subsystems for all SCADA systems: remote terminal unit, RTU, and master terminal unit, MTU. The communications interface and the man/machine interface are discussed in the next section.

Remote Terminal Unit, RTU:

The standard functions available in conventional, hardwired logic RTU are: data acquisition, operation of controls, management of data collected, and communications protocols for Master/Remote interchange of information. Microprocessor-based RTU devices will provide in addition to these standard functions, some of the following new functions: sequence of event recording, closed-loop control, local data collection and logging, equipment maintenance records, load management, digital metering, and digital relaying. A variety of design goals and approaches have been taken into account in the design of presently available RTU devices.

One class of RTU's is based on standard microprocessors such as the Intel 8008 and 8080, or the Motorola 6800. Examples of these units are the

following: Leeds & Worthrup model C2040, Westinghouse Redac 800, Quindar QUICS-1, Camco CAM/DAC series, and the Darcom D1100 series. A second class of RTU devices is based upon special purpose microcomputers built in-house by the RTU manufacturer. Examples of this class are the following: TRW 2000, Hitachi MIDIC-00, Control Systems Industries CS18000, and Quindar Quindette V. Most of these systems are based upon bipolar technology and have microprogrammable architecture. In almost all of these applications I/O functions and the data communications functions are handled by microprocessor-based controllers rather than hardwired digital logic. This approach achieves greater flexibility than the hardwired controllers. Each of these systems have some unique features relative to data handling, communication protocols, message formats, etc., and therefore are not compatible with each other. The design of programmable RTU devices will provide some opportunity to overcome the problems caused by the lack of industry standards.

Master Terminal Unit, MTU:

Master Terminal Units are of two types: stand-alone or integrated with centralized energy control centers. Examples of free-standing units are: Westinghouse REDAC 800 and Quindar QSS-4 systems. Microprocessor applications in stand-alone systems relate to communications interfaces to the RTU devices and to improved man/machine interface to the operators. If the MTU is integrated with an energy control center, a microprocessor may be used to realize the communications protocol required by the central host computer system, and to emulate the specific I/O requirements of the host computer. Thus the MTU systems may in the simplest case have a single microprocessor, and in the more complex designs consist of a network of microprocessors operating in a multiprocessor mode.

III-4. Man/Machine and Communications Interface Substations

These two subsystems are found in almost all of the various control and protection systems discussed previously. In each application, there will be unique requirements and characteristics. However, there are some common characteristics that are required in any application. These common characteristics relative to man/machine and communications interfaces are next considered in the context of the application of microprocessors.

Man/machine interface:

One of the most important aspects of the design of power system control equipment is the provision of an effective interface between the equipment and the personnel who operate the system. It is essential that the operator acquire and maintain confidence that the system is performing reliably and the responses to his/her commands are performed in a timely fashion. The functional requirements for such a man/machine interface are [1]:

- system operator functions
- on-line diagnostics
- program development
- system maintenance
- "on-line" operator training

Most of these requirements can be met using "intelligent" terminals. The typical "intelligent" terminal is microprocessor-based and can be programmed by the user. Although there are today a large number of "intelligent" terminals on the market, there are very few terminals which have been designed with the control and protection of power systems in mind. Examples of the latter terminals are: Aydin Controls model 5217 and Intelligent Systems Corporation Intecolor 8001. The use of "intelligent" terminals, a CRT display and keyboard integrated with a microcomputer, can significantly improve the interaction between the operator and the system for which he/she is responsible. Some of the parameters of this interface are:

- *operator/system dialogue
- *cursor control
- *format design
- *manipulation of the display formats
- *system response
- *device control
- *alarm philosophy
- *human factors engineering parameters

The role of the microprocessor in these applications includes communications, I/O processing, and general device control logic implementation.

Communication Interface:

The complexity of the communications interface depends upon the data interchange requirements of the particular protection and control system. The most complex communications requirements occur in SCADA systems between the RTU and MTU units, and in connection with Energy Control Centers between Data Acquisition Systems and the host computers. Typical requirements for a complex data communications interface are [12] as follows:

- *interface to multiple host computers
- *buffer data to and from channel adapters
- *transfer data between host computers
- *manage switching of redundant communications lines
- *detect data transmission errors
- *control and monitoring of modems and other communications equipment

Microprocessors can be applied to satisfy all of these requirements. The applications typically are either a communications controller or a monitor for data communications devices. Typical control applications are in message switching and programmable modems. Microprocessors are used to monitor the operation of UART's, USART's, multiplexers, and communications protocol chips. The flexibility of microprocessors provides a wide variety of possible applications to these communications problems.

IV. GENERALIZATION OF MICROPROCESSOR APPLICATIONS AND ARCHITECTURES

The examples of microprocessor applications discussed in the previous sections illustrate the wide range of system configurations which have been considered. The design of such systems is greatly simplified by the availability of a wide range of LSI chips performing supporting functions. This section deals with generalization and classification of microprocessor configurations and architectures appropriate to the problems of controlling and protecting electric power systems. The

following four functions are thus identified:

- *I/O handling
- *data communications
- *digital signal processing
- *digital controller

I/O handling is performed using a number of special function LSI chips such as: interrupt controllers, serial and parallel I/O ports, DMA controllers, memory controllers, CRT controllers, etc. Microprocessors are generally used to monitor and control the operation of these special LSI chips. In more sophisticated applications, microprocessors are also used to emulate the data, address, and control busses of some computer systems to provide for more efficient and flexible handling of I/O between dissimilar main processors. In these circumstances, microprogrammable architectures are used.

Data Communications are heavily supported by microprocessors and special purpose LSI chips. Today a wide variety of supporting chips are available, such as: USART's, UART's, synchronous communications interfaces, modems, multiplexers, line protocol units. In electric power system applications, most of the needed communications processing is accomplished using either software or firmware. Thus there are a number of different standards and characteristics. A wide variety of different communications media are also used. Voice grade telephone lines, microwave radio and power line carrier channels are the most commonly found media. Optical fibers and satellite communications are also being considered. Although a number of different data communications standards are employed, the RS 232C is the most widely used. The data rates used typically range from 1200 Baud to 9600 Baud. There are a number of different standards used for message formats. Sophisticated microprocessor applications for modem controls and multiplexing have been used only a little to date.

Digital Signal Processing is becoming an interesting and important area for applications of microprocessors in electric power systems. Digital protection and digital metering require the use of digital signal processing systems. Clearly, microprocessors can be readily applied to these tasks. Special purpose digital signal processing chips available are: Fourier transforms chips, signal correlators, fast multipliers, hardware floating point packages. These chips were developed in response to well-articulated needs, primarily in the communications area. However, the needs for specialized processing functions in the area of power system control and protection have not yet been adequately identified and promoted.

Digital Controllers are frequently more easily designed and implemented using microprocessors than with hardwired digital logic. Such software and firmware-based designs offer great flexibility for such applications. Study of the literature reveals that many different microprocessors have been used for digital controllers for power system applications. However, very little is found in the published literature relating to procedures for developing specifications for the microprocessors for these applications. The reasons for the choice of a particular microprocessor for a specific application are not generally given in the literature. The characteristics commonly found in microprocessors

used for these control applications are:

- *8- to 16-bit word length
- *microprogrammable
- *bit slice configurations
- *single bus architectures
- *limited local memory

Architectural characteristics that have been rarely considered to date are:

- *distributed processing
- *distributed data bases (physically)
- *multibus structures
- *mixed memory speeds and technologies

The applications and architectural classification described in this section can be used for additional improvements in the flexibility and utility of microprocessor applications to the control and protection of electric power systems. Such an approach is described in the next section.

V. NEW DESIGN CONCEPTS

The previous discussion has shown that for the most part to date, microprocessors have been applied to implement one-for-one replacements for the prior generation of analog or digital equipment. Standards have not been developed in these applications, nor have general specifications for suitable microprocessor systems and architectures evolved. The various decompositions of the power system protection and control problem have suggested that some new design approaches might be developed. An approach to the standardization of microprocessor applications to this problem together with some new design approaches for microcomputer applications is the subject of this section.

Standardization of microprocessor applications is needed and required in any area which anticipates a broad range of applications of large quantities of microprocessors. Such standardization will enable system designers to produce solutions which will offer the desired flexibility, reliability, availability, maintainability, and security. The development of such standards will identify a set of problems to be solved. These problems can be usefully divided into two classes: One, which can be reasonably solved with existing technology; two, those which require or could benefit from the development and application of new technology. It is believed that the areas of communications and process control can be readily standardized. The areas of I/O controllers and signal processors will probably require some new developments in both microprocessor and supporting function chips. It is the authors' strong perception that the proposed standardization of microprocessor applications to the electric power control and protection systems would encourage more active involvement of the semiconductor industry in producing products tailored to the particular needs of the electric utility industry. The active interest of and participation by the electric power industry with the semiconductor manufacturers in addressing these problems would have a very beneficial effect. It is believed that research and development activities related to the analysis and generalization of microprocessor applications are necessary first steps toward the desired standardization.

New Design approaches are implicitly suggested

in the initial discussion of this paper. It is evident from the suggested decomposition structures that new strategies can be developed for organizing the control and protection functions. These new strategies would evolve based upon an appreciation of the capabilities of microprocessors relative to the basic functional requirements for control and protection. In particular, the microprocessor makes it possible to consider distributed and decentralized approaches to this problem that were not possible with minicomputers. Most work to date has been oriented to a centralized rather than distributed system design. It is the authors' opinion that the potential of the decentralized approach merits further research. There are at least four reasons for such an opinion. First, it is very likely that new theoretical developments in decentralized control theory, as well as theoretical considerations of new functional realizations within the electric power system will favor a decentralized approach. Developments in microprocessors, as well as developments in distributed processing architectures will be able to meet the needs for a decentralized approach to this problem. Finally, since so little has been done to date in this area, investigation of the decentralized approach is a promising and challenging endeavor.

The authors have been involved for several years in investigating a distributed processing microprocessor-based, hierarchically-structured approach to the problem of control and protection of electric power systems. Results of the initial investigation have been reported in several papers [13,14,15]. A block diagram of such a system is shown in Fig. 2. This system was conceived for use in transmission substation automation, but the general approach can be used in other applications as well. The reasons for distributed processing have been discussed earlier in this paper. The hierarchical structure was chosen because the power system to be controlled and protected is itself hierarchical in nature. This is evident from both the control and decision-making point of view.

VI. CONCLUSIONS

Conclusions following from the above discussion are:

- *microprocessor applications to electric power system control and protection are a promising area of development;
- *a better understanding of electric power system functions and structures are necessary to fully utilize the microprocessor technology;
- *the generalization of microprocessor applications as replacements for the classical analog and digital systems is an important step toward needed standardization in this area;
- *new design concepts are needed to fully exploit the potential of microprocessors for use in the control and protection of electric power systems.

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