

J. S. Deliyannides, M. Kezunovic*, T. H. Schwalenstocker

To be presented at IEE Conference on
Power System Monitoring and Control,
London, June 24-26, 1980.

Westinghouse Electric Corporation, USA

ABSTRACT

Computer applications in control and protection of electric power systems have been heavily affected by developments in microprocessors and microcomputer systems. Microprocessors provide design flexibility as well as improved utilization of the hardware and software resources which can reduce system cost. Numerous applications of microprocessors in Supervisory Control and Data Acquisition (SCADA) systems, as well as Digital Protection (DP) systems have been reported during the past five years. This paper reports on the initial system design for a new digital substation control and protection system. The work reported is being performed by the Industry Systems Division of the Westinghouse Electric Corporation under contract from Electric Power Research Institute (EPRI). The main system design goal is to integrate, in an all-digital system, the control and protection functions. Such a design promises to improve operational performance, reliability and maintainability and to reduce system cost. Distributed microprocessor system concepts, high performance 16-bit microprocessors, high level languages and fiber optic communications are some of the techniques and technological advances used to achieve the design goal.

INTRODUCTION

In the past several years, a number of projects related to substation digital control and protection have been planned and completed by utility companies and research organizations throughout the world. Several of these projects resulted in the development of prototype systems based on microprocessor technology and in some cases, fiber optic links were used. The major thrust was to develop either a digital protection system or a substation control and/or data acquisition system using the latest technology. The concept of integrating control and protect functions was not developed and implemented on a significant scale. Therefore, the EPRI project is probably the first attempt to design a conceptually new integrated control and protection system using the latest technological developments. However, the results of the recent projects in this general area of substation control and protection have contributed to the confidence levels needed to finally initiate a research project for an integrated system. The following review of the state of the art in this area is based on the published reports.

The area of digital relaying has been developing since the late sixties (1). The first prototype system, the Westinghouse PROGAR 70 system (2), represents a successful feasibility study. Microprocessors have been used in this area since the mid seventies (3). Recently published reports are related to the development and testing of a microprocessor-based relay by American Electric Power Service Corporation (AEP) (4) and by Washington State University (1). A minicomputer-based digital relay has been developed and tested by General Electric Company (GE) (1). There are a number of reports on microprocessor based relays developed and tested in Japan (1) by Tokyo Electric and Kansai Electric Utility companies in cooperation with Toshiba, Mitsubishi and Hitachi manufacturing companies. Digital relaying prototype systems were also developed in Canada by

* Under contract from University of Kansas, USA

Saskatchewan Power Corporation (5), in England by Imperial College (6), and in Germany by the Siemens Company (7).

Applications of microprocessors to the development of individual control and data recording functions were also recently reported (3). A microprocessor-based revenue-metering algorithm was developed and tested by Ohio University. A microprocessor-based alarm logger using fiber-optic communication was developed and tested by Bonneville Power Administration (BPA). Rochester Instrument Systems has developed a microprocessor-based Sequence-of-Events Recorder. Microprocessor-assisted Check Synchronizing was designed at the University of Roorkee, India. A microprocessor-based tap-changer controller was designed by the Hydro-Quebec Institute of Research, Canada, and by the Capricornia Institute of Advanced Education, Australia.

The area of Supervisory Control and Data Acquisition (SCADA) Systems has been widely influenced by the development of microprocessors. There are a number of microprocessor-based Intelligent SCADA Remote projects (3) reported by Westinghouse, TRW, Leeds & Northrup, Quindar, Control System Industries, Harris, Hitachi, and BPA. In this general area, there are also important developments in Man-Machine interfaces. Microprocessor-based intelligent terminals are manufactured today by several dozen companies in the U.S.A. alone.

Integrated substation control projects are of particular interest because both microprocessor and fiber optic technologies were used there. Interesting implementation results are published (8) on BPA's Substation Integrated Control System (SICS), GE's PROBE System, TriState Generation and Transmission Association's Wray Substation Project, AEP's project (3) and the Public Service Electric and Gas (PSE&G) project (9). Several reports indicate similar efforts by the Central Electricity Generating Board (CEGB) in England and by the Electricite de France (EDF) in France. Some of those projects utilize both microprocessors and fiber optic technology.

Finally, in the area of Integrated Control and Protection Systems, there are very few published reports related to prototype systems. An interesting proposal was published by AEP (10). The only prototype system was designed and tested jointly by the Kansai Electric Power Company and Mitsubishi Electric Corporation in Japan (11).

In summarizing, it is evident that a significant number of projects have been completed and reports have been published. Microprocessor and fiber optic technology were used in some of the prototype installations. However, an Integrated System of the scale of the EPRI Substation Digital Control and Protection project has not been previously designed and implemented.

SYSTEM DESIGN GOALS AND OBJECTIVES

System design goals and objectives are to improve system characteristics such as utilization, flexibility, accuracy, security, availability, reliability, maintainability and cost. It is believed that these improvements can be achieved if the system encompasses the following features.

- System is all-digital.
- System is integrated.
- System provides new functions.

The all-digital design enables use of processing power, speed and extensive data manipulation capabilities to achieve flexibility, availability and security not found in conventional systems. It is also important to note the decreasing cost of the LSI components used for the digital design which can favor the all-digital approach over the conventional, hybrid design.

Integration of the protection and control functions implies possibility for better coordination of the two basic functions. This enables optimization of the control and protection strategies to provide desired performance of the substation line switching and voltage transformation functions. Additional benefits are better utilization, flexibility and reduced cost of an integrated design compared to the segregated conventional approach.

New functions are possible to implement because of the two system features already mentioned: digital and integrated design. Particularly important is availability of a common data base which enables creation of data files not previously available. Additionally, it is possible to develop quite sophisticated man-machine interface and improved monitoring functions. Data validation can be improved using data estimation techniques. System operation monitoring is enhanced using self-checking and fault-tolerant techniques.

SYSTEM FUNCTIONAL REQUIREMENTS

The functional requirements consist of those functions now being performed through conventional protection and control devices plus additions which may be feasible because of the flexibility of digital processors. The requirements were developed after extensive consultation with six electric utility advisors to reflect a wide range of needs and practices. They represent a reasonable compromise between utility requirements and preferences vis-a-vis cost and complexity of implementation. A number of functions were defined and their requirements were specified. These functions have formed the basis for further detailed system design. The functions fall under four general categories:

Protection Functions

These functions initiate high speed tripping of circuit breakers at each terminal when a fault is detected anywhere along the protected zone of the corresponding component. They are:

- Line Fault Protection
- Transformer Fault Protection
- Bus Fault Protection
- Shunt Reactor Protection
- Breaker Failure and Fault Protection
- Transfer Tripping

Pilot and non-pilot protection with delayed remote backup protection are provided for lines. Transformer trip logic includes over-excitation, differential overcurrent, and time overcurrent protection. Phase differential protection with ground overcurrent as backup, and transfer tripping features are also provided.

Automatic Control Functions

These functions carry out control operations at a rate lower than protection functions. Automatic control functions are:

- Local Control of Voltage and VAR Flow
- Tie Tripping
- Load Shedding
- Automatic Reclosing
- Synchronism Checking and Synchronizer Closing
- Automatic Switching Sequences

Voltage or VAR flow are controlled by operating transformer tap changers or by switching capacitor or reactor banks. Tie lines may be tripped on sustained heavy power outflow and system underfrequency. Blocks of load may be dropped and restored as system frequency crosses predefined levels. When line or, optionally, bus breakers trip, they may be reclosed n times automatically. Synchronism conditions are checked prior to manual and, optionally, automatic closing of circuit breakers. Finally, sequences for automatic reconfiguration of faulted equipment are provided.

Monitoring Functions

The monitoring functions include supervision and periodic testing of the integrity of system components. Monitoring functions are:

- Pilot and Transfer-Trip Channel Monitoring
- Load Monitoring and out of Step Protection
- Monitoring and Control of Breakers and Switches
- Inferential Measurement Check
- Transformer Overload and Tap Position Monitoring
- Self Checking

Data Acquisition, Recording and Displaying

Under this category are grouped all the functions which pertain to the interfaces between the protection and control system and the external world—SCADA masters, local and remote operators as well as all the information displayed to them. These functions are:

- Local man-machine Subsystem.
- Remote SCADA Interface.
- Alarming.
- Data Logging.
- Revenue Metering.
- Recording and Indication of Sequence of Events.
- Oscillography.
- Line Fault Location Estimation.

SYSTEM ARCHITECTURE

The successful design of this system depends on the appropriate grouping and configuration of system modules and allocation of the functions to these modules. These topics are described in this section.

System Configurations

The system concept is an organization of multiple microprocessors performing protection and control functions and connected by optical fiber links to remote data acquisition units distributed in the substation switchyards.

The options involved in distributing the data acquisition units in the substation switchyards and interconnecting them with the protection processors are of particular interest because of their effect on system cost and performance.

Data gathered at any point in the switchyard must be distributed to two different protection functions. All breakers connected to a bus provide data for the protection of that bus as well as for protection of either a line or a transformer. The center breakers in a breaker-and-a-half bay provide data to either of two different protection processors. Figure 1 illustrates the overlapping zones of data collection for the basic protection functions in a typical substation.

Figure 2 shows five different ways in which data from one breaker may be distributed to two independent function processors.

A type 1 configuration uses two completely independent paths. This is the greatest possible separation of functional hardware and the most modular system. It is easiest to adapt to different substations and to expand as a substation grows.

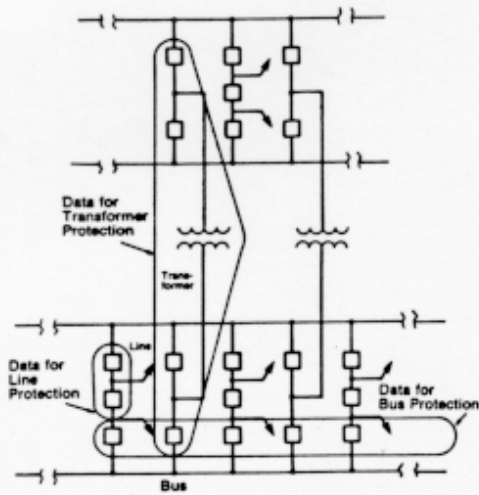


Figure 1 Functional Grouping Of Data In A Typical Substation

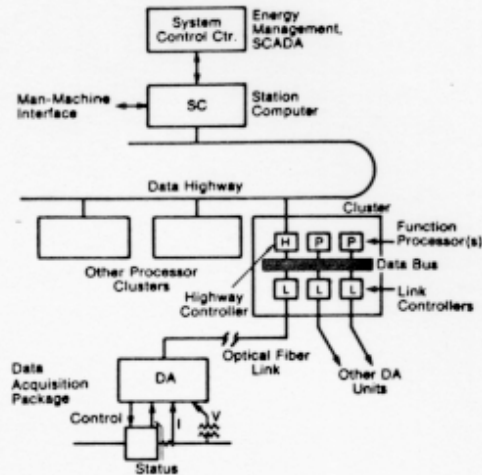


Figure 3 System Configuration

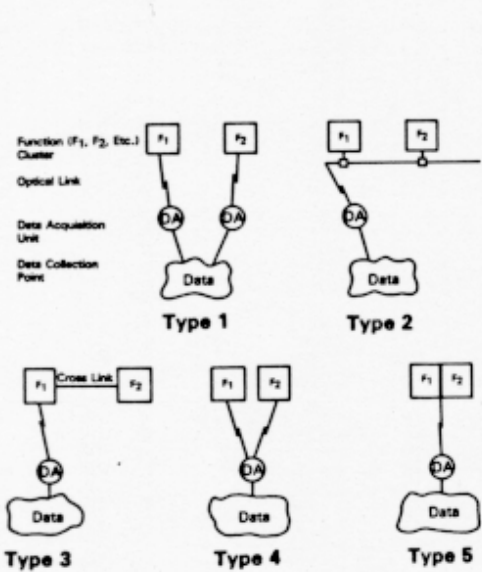


Figure 2 Configurations For Distributing Common Data

A type 2 configuration has a single data acquisition unit and optical link which at some point is converted to an electrical signal tapped by the two different function processors. This configuration eliminates hardware duplication of data acquisition units and links at the expense of somewhat more complex link controllers at the function processor level.

A type 3 configuration also uses a single data acquisition unit and optical link but the data that the second function processor requires is provided via a crosslink. This configuration requires the least hardware but is the least modular. It also introduces new problems due to delay in retransmission of data from the first cluster to the second and the dependence of the second cluster on the proper operation of the first.

A type 4 configuration has a single data acquisition unit with separate links to two different function processors. It eliminates data acquisition, but not data link, duplication.

A type 5 configuration has a single data acquisition unit and optical link which deliver data to be shared by two function processors which are closely linked together in one cluster. Within the cluster, each protection function is assigned to an individual protection processor but below that level, specific hardware is not segregated by protection function.

The main goal of the system configuration development has been to share data acquisition and link hardware while retaining reasonable modularity so that the system is reliable, adaptable, expandable, and easy to maintain.

Data Communication

Three different types of communication paths in the system are shown in Figure 3.

Data Links. Data links are dedicated, point-to-point, serial optical communication connections between data acquisition units in the field and function processors in the control house. Optical communication was chosen because of its immunity to high voltage switching transients and other types of EMI found in the substation switchyard environment. The physical link consists of a cable with two optical fibers, one for transmission in each direction. Controllers at each end of the link use VLSI advanced protocol chips to implement an SDLC protocol on the link and can transmit and receive simultaneously. An SDLC protocol was chosen because it is widely accepted, efficient at the required message lengths, reliable due to CRC error detection, and well supported with LSI technology.

System Bus (S-Bus). The S-Bus ties the various devices at the function processor level together into clusters. The S-Bus is a parallel, 16 bit, TTL level data bus with a speed of 0.1 to 1.0 microseconds per memory operation. The function processors, link controllers, and highway controller shown in Figure 3 all interface to the S-Bus with shared memories. Data movement among these S-Bus devices can be controlled either by the device requesting or supplying the data, or by a bus master. The first method results in a minimum number of devices being involved in the data and link controllers, but it also spreads the control of the data flow among several devices that may need to be reprogrammed when the system is changed or expanded, and it adds some complexity to each device's bus interface. The initial system design will use the bus master approach.

Data Highway. The data highway is a serial multidrop communication system connecting all clusters together and to the station computer. It is defined in four ascending levels: physical medium, access procedure, message protocol, and user interface. Coaxial cable was chosen as a physical medium for use within the control house environment because it is reliable and cost effective. The bus access procedure will be determined after the completion of an analysis comparing the requirements of communication among clusters and between clusters and the station computer. These requirements are affected by function allocation and system configurations which are discussed elsewhere. The message protocol will be a bit oriented SDLC-like format with address field modifications. This format was chosen for the reasons cited in the previous discussion of data links. The user interface is a shared memory which allows unrelated activity to take place on the S-Bus while highway transactions are in progress.

Function Allocation

The functions previously described must be properly allocated among the various levels of the hierarchy illustrated in Figure 3. The objectives of this allocation are to improve speed of response, to simplify system understanding and software implementation, to improve ease of reconfiguration upon detection of subsystem failures, and to minimize storage requirements.

For speed of response, it is desirable to locate functions at the lower level of the hierarchy. For availability of data and ability to access data quickly and make decisions centrally, it is desirable to locate functions at the upper level. A compromise must be reached that splits the allocation of functions according to their characteristics.

Each function can be divided into modules which perform distinct classes of operations. These are:

- The acquisition and processing of input data.
- The calculations or logic required to generate either operator warnings and alarms or protection and control actions.
- The coordination and carrying out of control actions.

- The communication to the outside world including operator inputs and CRT display outputs, and interfaces to SCADA master and protection engineer's console.

Each function was decomposed into its individual modules and each module was then allocated to a particular level in the hierarchy.

At the lowest level, the data acquisition takes place periodically and synchronously at the rate of 16 samples per cycle. Instantaneous values of currents and voltages as well as breaker and auxiliary equipment status are deposited in buffers at the protection processor clusters.

The protection function algorithms and control functions which involve information from a single breaker or bay only, are performed at the cluster level. RMS values and other power system parameters are calculated and transmitted to the station computer at a lower rate. Oscillography data and sequence of events data are recorded at the cluster level and transmitted upward for display at the station computer level.

Other controls, requiring information from locations throughout the entire substation, are performed at the station computer level. All operator inputs and displays, as well as interfaces to SCADA master and protection engineer's console are located at the station computer level. Operator control requests are transmitted to the cluster level for execution by the protection processors.

System Interfaces

System interfaces fall into two broad categories: internal and external interfaces.

Internal interfaces exist between three basic locations within the system: substation computer, processor clusters, and data acquisition units. The physical data paths are the data highway, the cluster S-Bus and the data link between the data acquisition units and the cluster.

External interfaces are connected either to the internal busses within each of the locations or to the physical link between them. The man-machine interface and the interface to the remote load dispatching center are connected to the internal bus of the substation computer. The interface to the field transducers is connected to the internal bus of the data acquisition units. To accommodate coordination between two systems at opposite ends of a transmission line, pilot and transfer trip communication channel interfaces are provided. These interfaces are connected to the cluster S-Bus. Interface to a cluster of a different type is provided at the data highway level.

SYSTEM HARDWARE, COMMUNICATIONS AND SOFTWARE

Microprocessor

The microprocessor used to implement the protection algorithms and related functions in this system must meet the following requirements:

- Have the speed necessary to implement its function 16 times per power cycle.
- Be available for field installation in 1982.
- Be compatible with an overall protection processor function reliability goal of an MTBF of 10^5 hours at 40°C.
- Have a low enough cost so that the total system can compete in cost with existing relay systems.

The last two requirements can only be met using VLSI microprocessors. The speed requirement rules out all but the latest generation 16 bit microprocessors.

These processors have also been evaluated in terms of a number of other factors that were considered desirable. These can be grouped into four areas: architecture, product family, support, and vendor.

Desirable architectural features are powerful addressing modes, symmetry in registers and instruction set, and traps for error recovery and future instructions.

The processor family should include devices for memory management, DMA, and real arithmetic processing.

Support products include real time operating software, high level language compilers, development systems both for initial development and for field use, and PC board level products for use in the system.

The Motorola 68000, Zilog 28000, Intel 8086, and TI 9900 meet the requirements with the possible exception of speed. Benchmarks based on the actual protection algorithms and related functions are now being prepared for this test. Based on relative speed comparisons and the other considerations listed as desirable, the Motorola 68000 has tentatively been chosen to implement the protection processor function.

Optical Communication

The optical communication links between protection processor clusters and data acquisition units have the following requirements:

- . Data transmission rate of 1MHz.
- . Bit transmission error rate of 10^{-9} .
- . Low maintenance cost.
- . Immunity to high voltage switching transients and other EMI sources.
- . Length up to 500 meters.
- . Compatibility with substation installation requirements.

The link controllers consist of an LSI advanced protocol serial interface chip driven by an eight bit microcomputer with DMA. Manchester encoding is used on the link. The optical source is an infra-red LED and the detector is a PIN diode. These devices are reliable, low cost, long lived and operate over a wide temperature range.

The optical conduction medium is an optical cable with two silica fibers (one for each direction). The choice of cables is determined by their operating temperature ranges, general construction, price and optical specifications. Performance is considered last because most commercially available fibers surpass the requirements imposed by the relatively short distances (500m) and modest data rate (1MHz) of this application.

System Software Requirements

In the design and implementation of any real time computer system, the software considerations are of extreme importance. There are two classes of software: First, there is the totality of programs which describe all the application functions; second, there are those system software programs and services which provide the on-line and off-line environment in which the application programs are developed, tested and executed.

The selection of a language for application programming has been a major area of project investigation. Key elements considered as goals are: reliability, maintainability, modularity, documentation, general industry acceptance, portability, program and programmer efficiency at the anticipated levels of skill. These goals are achieved through a high level language. The particular language selected is Pascal. It has an easy to understand syntax contained within a rigorous block structure which supports all the needed control statements and which permits programmer defined data structures.

The system software requirements are different at the various levels in the hierarchy of processors.

At the data acquisition level the problem is one of synchronization and timing. When synchronized, the data acquisition unit automatically puts on the link all of its analog and digital signals once every sampling period.

The programs at the protection processor cluster level are characterized by sequential processing. However, processing cannot begin until all the data required for the calculations of the current sampling interval are present. A facility for signaling the availability of all data is required. Software must also be provided to insert control commands into the data link buffer in response to output from the protection algorithms. Another requirement for the protection processors is time delay countdown and program resumption. Many time delays are used in the logic of control algorithms. The system should have the capability of maintaining several concurrent time delays expiring at different intervals. Another requirement is the ability to communicate signals between adjacent processors. This communication is either through a cross link or through the data highway.

At the substation processor level, because of the greater variety of functions executed, there is need for concurrent multilevel processing with independent event driven input-output facilities. Timed task initiation and time delays are also required. The functions which require I/O facilities are the operators console interfaces, the remote SCADA interfaces, the local output devices (printers, CRT's, etc), and the interface with protection processor clusters through the data highway.

What has been discussed so far are on-line system software requirements. In addition to these, there are requirements for the efficient generation, debugging, system testing and modification of application programs. All microprocessor manufacturers provide conventional software development facilities which include assemblers, compilers, loaders, instruction simulators and debugging packages. In addition, for purposes of system testing of application programs some kind of simulation is required so that the test environment will be as realistic as possible.

SYSTEM PERFORMANCE EVALUATION

Given below is a brief discussion of the most important system performance parameters with an explanation of their relationship to the system characteristics.

Utilization of the equipment is optimized by using the same signals and processing devices for multiple functions. In an integrated system, signals are brought to a central location through multiplexed fiber optic links and there used by all functions requiring these signals, e.g. the same signal is used by both protection function and SCADA.

Flexibility is provided by virtue of the fact that the system is programmable and integrated. Programmability, either in software or firmware form, enables changes to be made when system operational parameters change. The fact that the system is integrated provides flexibility in system performance evaluation because changes in the system can be easily located and tested against all of the other functions which can be affected by these changes.

Accuracy is another advantage of digital systems. In such systems, decisions can be made based on characteristics of the shape of input signals. Accuracy in digital systems is further improved over conventional systems through error detection and correction techniques on transmitted data.

Security is achieved through a better decision-making process. For example, it is possible to run several protection algorithms in parallel and compare the results so that control is taken only if outputs of the related decision processes are in agreement.

Availability is improved considerably through self-checking and prompt error detection. This provides better system availability even in cases where the reliability of individual devices is relatively low. Automatic failover also enhances availability.

Reliability of digital devices is, in general, quite good. Equipped with self checking features, digital relays can indicate their own failure. This improves the meantime to repair (MTTR) as well as the repair strategy. Therefore, digital devices can provide an improved availability.

Maintainability is probably easier in conventional systems than in computer based systems. However, compact packaging of computers can provide ease of replacing of the faulted parts. This of course assumes additional features which provide a straight forward procedure for locating the faulted module.

Cost reduction benefits are achieved through the use of new technology, and new design concepts. The cost for new 16-bit microprocessors, new LSI communications and I/O chips and fiber optics is rapidly decreasing. Integration of protection and control functions plus self checking capability also reduce both initial equipment cost and cost of testing, maintaining, modifying and expanding the system.

CONCLUSIONS

The work done on this project to-date, has been related to the definition of system functional requirements, the study of economic and technical feasibility of the use of microprocessor and fiber optics technologies, the investigation of system architectures and the specification and initial functional design of equipment and software modules (12, 13). The next phase of the project is the detailed design, implementation, in-house testing, installation and extended field testing of a prototype in an actual Utility site. Further progress on this project will be published in the future.

The results obtained so far are encouraging. It appears that the approach taken is feasible both technically and economically. The constantly decreasing cost of LSI and fiber optics technologies, the flexibility of digital programmable systems and the concepts of integration of protection and control functions, promise a successful implementation of an integrated microprocessor based protection and control system.

REFERENCES

1. Rumer, D. I., Kezunovic, M., 1979, "A Survey and Classification of the Digital Computer Relaying Literature", Paper presented at the IEEE PES Summer Meeting, Paper No. A79 417-7, Vancouver, B.C.
2. Udren, E. A. and Chambers, E. H., 1976 "Relaying by Digital Computer-Experimental Field Trials and Future Prospects", Presented at the EEI Electric Systems and Equipment Meeting, Los Angeles.
3. Rumer, D. I., Kezunovic, M., 1979, "Microprocessor Systems and Architectures for Applications to the Control and Protection of Electric Power Systems", ACM Symposium SIGSMALL '79', Dallas.
4. Phadke, A. G., et al., 1979, "A Microcomputer Based Symmetrical Component Distance Relay", Proceedings of the IEEE 11th PICA Conference, Publication No. 79CH 1381-3-PWR, Cleveland.
5. Davall, P. W., Au Yeung, G. 1979, "A Software Design for a Computer Based Impedance Relay for Transmission Line Protection", IEEE Summer Meeting, Paper No. F79 622-2, Vancouver, B.C.
6. Cory, B. J., et al, 1979 "Development of a Dedicated Microprocessor Protection Relay", IEEE PES Summer Meeting, Paper No. A79 512-5, Vancouver, B.C.
7. Strecker, H. et. al., 1979, "Network Protection with a Process Computer", Paper presented at the CIRED Meeting, Paper No. 26, Brussels, Belgium.
8. Working Group of the Substations Committee, 1978, "Recent Field Experiences with the Automation of Substation Control", Paper Presented at the IEEE PES Winter Meeting, Paper No. A78 102-6, New York.
9. Castro, C. H. and Sottovia, P. R., 1978, "A Minicomputer Application for Substation Control", Paper presented at the IEEE PES Winter Meeting, Paper No. A78 102-7, New York.
10. Ibrahim, M., et al., 1979, "The Integrated Substation Concept Opportunities for the Future", Proceedings of the American Power Conference, Chicago.
11. Tanaka, K., et al., 1979, "Application of Microprocessors to the Control and Protection System at Substation", IEEE PES Summer Meeting, Paper No. F79 629-7, Vancouver, B.C..
12. Nilsson, S. L., 1980, "EPRI Research and Development for New Substation Control and Protection Equipment", IEE Conference on Developments in Power System Protection, London.
13. Udren, E. A., Sackin, M., 1980, "Relaying Features of an Integrated Microprocessor Based Substation Protection and Control System", IEE Conference on Developments in Power System Protection, London.