Microprocessor Applications to Substation Control and Protection

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Introduction

Since the mid-'70s, creative engineers have sought ways of using microprocessors to improve the control, protection, and monitoring of power substations. The following discussion is intended to survey some of the characteristics of microprocessor applications introduced over the last ten years and to point out the specific benefits received from these uses. For example, design advances in fault recording, computer relaying, and supervisory control and data acquisition (SCADA) systems have been tied directly to the availability of microprocessors and related digital technologies. These advances would be problematic at best if microprocessors were not available.

Possibly the most significant global advantage offered by microprocessor technology is that it has enabled us to consider system integration of the various automation and data-acquisition functions. By efficiently and cost-effectively combining functions in common hardware and software, one can achieve synergistic performance results and even perform functions previously unachievable. In particular, the concept of integration of several functions in one hardware solution provides for a very cost-effective design, which may be one of the main advantages of using the microprocessor-based technology.

In practice, clear advantages must be demonstrated by design engineers who wish to change from traditional to digital designs and who wish to integrate substation functions. Traditionally, electromechanical and static devices are not easy to integrate. One of the specific reasons individual functions have been separately implemented in substations is that ''analog'' designs are often most cost-effective when they perform a single function. This particular design approach emphasizes functional boundaries that are drawn between different equipment vendors. For example, vendors of control and data-acquisition equipment provide only one or two of the functions needed in a substation and are, in many cases, not interested in diversifying their offering to utilities. A specific company may provide a certain type of data-acquisition equipment and not at all be in the business of providing protection functions or communication equipment even though the functions require an identical data base for implementation. Obviously, for true integration to occur, it is required that vendors diversify product lines across functional boundaries.

Another perception that exists is that there are no ''cost benefits'' to functional integration in substations. While this may be true with many conventional designs, it is often not the case with well-designed digital systems. In general, the more functions that can be implemented in common hardware using the same or similar data bases, the lower the cost per function. Therefore, a significant advantage of integrated microprocessor systems for substations is the potential for lower cost.

Further discussion concentrates on specific design issues that illustrate some of the design characteristics and advantages achieved by using microprocessors. Specific examples related to the development of distance relays, distribution feeder monitoring and protection systems, and integrated control and protection systems for high-voltage substations are hereafter discussed.

Distance Protection of Transmission Lines

Implementation of a distance relay using digital VLSI technology is a good example of new design approaches that can be taken.

An important observation is that the relay continually samples input signals starting from the moment the relay is turned on. Therefore, input data is available for the entire history of the signal changes. However, for practical reasons, only a limited sample set is kept in a memory buffer. This memory is usually circular in a sense that whenever the buffer is full, the next sample sets are stored, overriding the ''old'' samples. This feature enables continuous monitoring of the transmission line loading, as well as capturing prefault and fault values in normal-to-fault transition of power signals.

Another common feature of microprocessor-based distance relays is the self-checking of relay health and operational status. This feature is extremely useful for testing and maintenance purposes and represents a

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major design advancement when compared to previous technologies. Also, a definite improvement is obtained in the area of operator interfaces. Extensive operator displays may be generated for reporting relay settings, operational state, and various power system signal measurements. Relay setting procedures may be significantly enhanced and simplified by using terminals with elaborate handling protocols for changing the settings.

Internal processing in a microprocessor-based relay is implemented by using various logic and arithmetic operations on signal samples. Relay algorithms are implemented by using software routines that are stored in relay firmware. A typical functional software flow diagram is given in Fig. 1. This figure suggests a unique flexibility feature of a microprocessor-based design where each of the processing steps in a relay algorithm may be provided as a separate software module. It enables a designer to easily change certain modules in order to accommodate different relaying requirements. In the case of a distance relay, different shapes of the relay operating characteristic, as well as different algorithms for voltage, current, and impedance measurement may be implemented by using the same basic hardware as well as the same basic software organization given in Fig. 1.

Finally, it should be understood that a microprocessor-based relay opens new strategies regarding functional implementations. A relay may be designed to perform some classical distance relaying functions, such as multizone protection with different communication options for transfer tripping/blocking functions. On the other hand, a very complex design may be implemented in a one-distance relay microcomputer. In this case, besides the basic distance relaying functions, other functions may be included, such as: local breaker failure protection, high-speed reclosing, automatic synchro-check, out-of-step protection, transient recording, fault location, SOE (sequence-of-events) recording.

It is important to note that this flexibility in the design enables quite a cost-effective distance relaying implementation. If only the basic relaying functions are required, then a low-cost 8-bit single-board microcomputer solution may be used. On the other hand, if a complex distance relaying design is required, then a high-performance 16-bit multimicrocomputer system may be required. This design might not be more cost-effective than an equivalent conventional design. However, by adding the extra functions, which are, in this case, available at no cost, the overall complex distance relaying design would be less expensive than a set of different conventional devices needed to perform the equivalent functions.

Distribution Feeder Monitoring and Protection

Microprocessors have opened new horizons for designers of monitoring and protection equipment for distribution feeders. It has been shown that conventional protection functions can be performed more efficiently and sensitively using digital designs. It has also been proven that new monitoring and protection functions can be implemented in digital designs that were previously impossible to achieve by reason of cost or technology. Examples of these advances include digital relays for distribution feeders, digital fault recording and analysis systems, and distribution automation systems.

A number of research and development efforts in this area have been undertaken in the past. An example of a large-scale investigation is several distribution automation projects such as EPRI/GE/TESCO and EPRI/Westinghouse/CP&L projects. An investigation by Texas A&M researchers has shown it possible to efficiently integrate numerous functions into one integrated system. The intent of this research is to show the feasibility and advantages of integrating substation functions into one hardware and

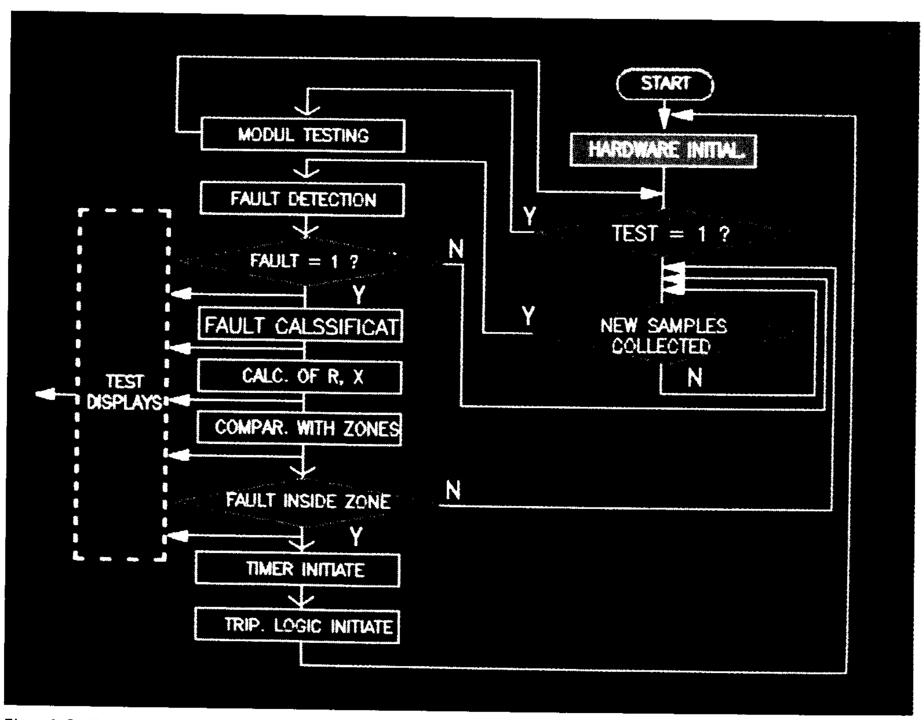

Fig. 1 Software flow diagram of a distance relay.

Table: FPMS functions and features.

Protection Features	Monitoring and Recording Functions
Phase/ground overcurrent protection	Pre-/postfault data recording
Programmable relay curves	Operator-selectable event recording
Remote curve setting	Event time tagging
Remote setting of coordination parameters	Feeder load monitoring
Analysis of faulted signal waveforms	Feeder harmonics/noise recording
Communication Features	
Remote, bidirectional communications	Program download capability
Local operator interface	Remote transfer of fault recordings

software design. Various protection, monitoring, and communication features given in the Table were selected for implementation in a prototype Feeder Protection and Monitoring System (FPMS).

The *overcurrent relay section* of the FPMS incorporated overcurrent protection and monitoring for all three phases and the neutral of the distribution feeder. The instantaneous and time overcurrent functions provide primary feeder protection equivalent to that offered by electromechanical systems.

The flexible time-current coordination curves stored within the relay represent traditional curve types. However, these curves may be defined as any single-valued function of current and are not restrictive to the inverse characteristics of conventional electromechanical devices. The relay uses one curve for the protection of all three phase circuits and can use a second curve for the protection of the ground circuit. Curves may be downloaded to the relay to update coordination characteristics if feeder conditions change.

The overcurrent protection algorithm was based on a cross-correlation technique for estimating the magnitude of primary feeder currents. Each of the four currents was sampled at 240 Hz and correlated with reference values. The resulting component magnitudes were then used in a Walsh magnitude estimation procedure to estimate 60-Hz component magnitudes. A table lookup algorithm continuously determined the time to trip for a specific calculated current magnitude above the fault pickup threshold. This table was designed to provide high resolution for low fault currents where an inverse curve is generally steep. The table lookup procedure permits custom coordination curves to be entered so that the relay was not restricted to the limited inverse curve characteristics of conventional devices.

The obvious advantages of this device included the ability to program the overcurrent section with any relay curve shape or combination of curves. Furthermore, curves could be modified at will either locally or remotely through the appropriate man-machine interface.

The FPMS *data recorder function* stored several types of information about each disturbance seen by the system. When a fault occurred, data including the time of occurrence, the maximum phase and ground currents, and the settings of the relay in effect at the time of the fault were all stored and associated with the disturbance recording. If no trip output followed the disturbance, the disturbance was classified as an event and stored. If any form of trip output was generated, the disturbance was classified as a fault, stored, and made available to operators. Additionally, the device initiating the circuit trip was identified along with the phase on which the fault occurred. Such values as the time to trip and breaker operation time were also noted.

An oscillographic recording of the fault data for all three phases and ground was stored. For long data records, a data reduction routine was used to discard repetitive data and conserve system memory. The advantages of this recording system are numerous. Fault data is made available to operators on demand for subsequent analysis of system operations and the nature of the fault. This data could be transferred through existing communication links to a remote site for detailed analysis by higher level computers. Bidirectional communications were available either locally or through telephone modem for remote data transfer.

A research-level algorithm for analysis of faulted signal waveforms was also implemented and demonstrated. This algorithm was intended for the detection of very low current faults on distribution circuits that might not be detected by standard overcurrent relaying devices. The probability of detecting very low current faults is significantly improved by the algorithm that is capable of analyzing fault waveforms and parameters that are ignored by conventional overcurrent protection systems.

The advantages of an integrated distribution feeder protection system are numerous. When digital techniques are used, it is possible to acquire and analyze significant amounts of important data that have been previously ignored or discarded. Detailed oscillographic data from faults can be made available at very low cost in an integrated system. The ability to install generic relay hardware, which can be programmed with protective curves and coordination logic, can be realized. The ability to interconnect protective devices with other substation automation equipment, such as SCADA systems, and the ability to remotely interact with protection and monitoring equipment is achieved. One can conceive protection and monitoring modules that can be installed and networked in a distribution substation as the station expands.

Other obvious advantages include the ability to perform more detailed real-time diagnosis of the health integrity of distribution feeders, the ability to monitor short- and long-term load trends on the feeder, and the ability to detect abnormal conditions such as excessive harmonic content. These can be made available at very low cost from the common data base feeding an integrated system.

Another advantage is the potential for improved protection reliability using digital system designs. Some feel that it is necessary to have separate electromechanical or static devices without common hardware in order to achieve adequate protection reliability. Careful analysis proves that an intelligent system capable of self-diagnosis, using a multiprocessor design, and capable of second contingency protection can offer significantly improved statistical reliability over a simple redundant electromechanical system.

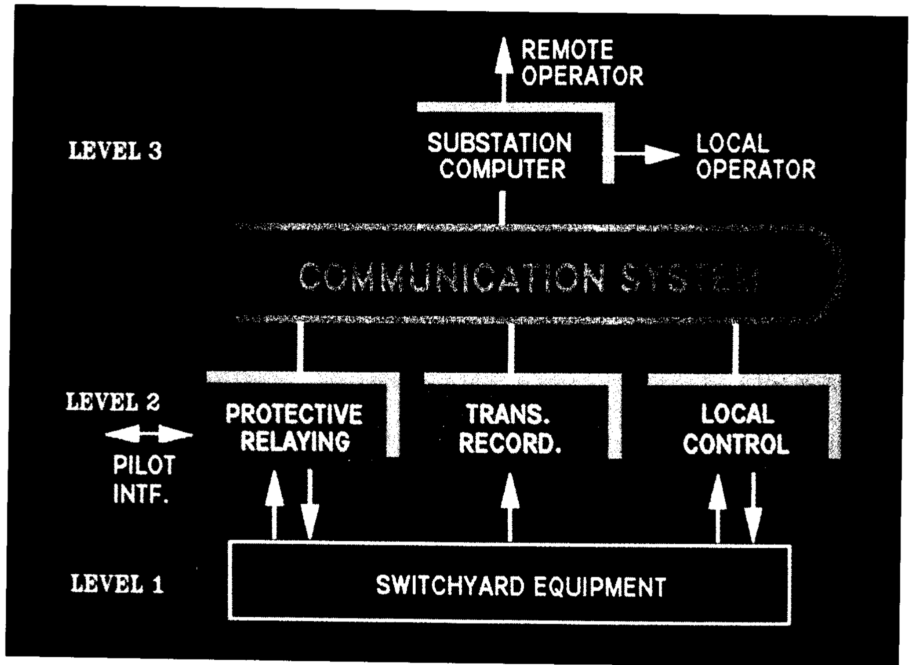

Fig. 2 An integrated control and protection system block diagram.

Integrated Control and Protection Systems for Substations

This system design concept calls for all substation automation functions to be resident in one multimicroprocessor-based, distributed processing system. Hence, the terminology "integrated" describes the fact that all the functions are included in one computer system probably consisting of a network of several microcomputers. The main design feature of the system is distribution of the processing power to a number of different microprocessors that are then interconnected. However, some researchers consider the term "coordinated processing" a more appropriate description. This term better describes the fact that a number of different functions are allocated to different processors in one system and the main characteristic of the system is coordination of different functions. The term "integrated" is often used even though the term "coordinated" could be assumed quite appropriate as well. An example of such a system is given in a block-diagram form in Fig. 2.

The most important observation is that the integrated system given in Fig. 2 has a hierarchical architecture. At least three different processing levels can be recognized. One level is the data-acquisition level, the other level is the processing level for certain time-critical functions, and the third level is the overall substation level. All adjacent levels are interconnected using various communication links. This communication facility is what makes the overall design appear as one system for the entire substation.

It should be noted that there are numerous ways of allocating substation functions to the processing levels within the system. These possibilities have yielded a number of different design approaches that have resulted in commercial products offered by several companies. Several developments, supported by EPRI, were introduced by Westinghouse Electric Corporation and General Electric Company. Long-term development has also been undertaken by the A.E.P. Service Corporation of Columbus, Ohio. Other companies that have worked on this concept for several years are: Electricite de France (with several French manufacturers), ASEA/BBC, GEC Measurements, Siemens, and several manufacturers in Japan.

Integrated design approaches would not have been possible without the availability of VLSI technology. In order to illustrate some of the resulting benefits, our discussion is divided into two major application areas: substation stand-alone applications and substation Energy Management System (EMS) designs.

Regarding the substation *stand-alone application*, it may be observed that an obvious advantage is a possibility to monitor the entire substation automation system as well as all of the power apparatus in a substation through a common data base. This data base is located at the third processing level in the integrated system hierarchy. This assumes that an operator may access the data base for a purpose of using this data for different monitoring and/or control purposes. However, this also means that an operator can access all the individual memories and processors in the system by using the feature of interconnection among different processing levels. This allows new possibilities in the area of system testing and maintenance, as well as in the area of systemwide change of programming or protection settings. Yet another important benefit is a possibility for data exchange among different application functions. This brings a number of options in implementing systemwide functions such as breaker failure, bus protection, automatic switching sequences, and interlocking schemes for switching equipment.

The second application aspect relates to the use of an *integrated system as a substitute for a remote terminal unit (RTU)* of an EMS. It should be noted that an integrated control and protection system (ICPS) can perform all of the functions found in an RTU design and, potentially, many more. Also, an integrated system design has improved performance characteristics for the functions that correspond to the ones found in an RTU. An example is the data-acquisition interface for analog input signals. The integrated system provides for higher sampling rates of input signals. This provides better accuracy for a wide dynamic range of the input signals, including signals corresponding to both normal and fault conditions. The design issue is instantaneous signal sampling on all input channels versus signal scanning provided in RTUs. One obvious conclusion is that it may be cost-effective to substitute RTUs with an ICPS design. The most promising area in this respect is a study of the use of an ICPS to execute certain EMS control center functions using a distributed processing approach. In this case, a major benefit would be the unloading of the control center computer from the processing load and redistributing this load to the quite powerful processing units within an ICPS. Some examples of this approach are decentralized transient stability control and hierarchical state estimation implementations.

Conclusions

This discussion has attempted to show the versatility of power system automation designs achieved by using third-generation digital technology, namely VLSI technology. It has been illustrated how the new technology can bring cost/performance improvements through new design methodologies. In particular, some benefits in the area of implementation of new concepts, not feasible with the earlier technologies, are outlined. However, despite a strong impact that is expected on power system automation from the introduction of the VLSI-based products, it is still believed that a number of different problems have to be further researched and resolved.

For Further Reading

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