The Next Generation of Monitoring and Control Systems Using Synchronized Sampling Technology and Multifunctional IEDs

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Abstract

This paper discusses implementation of the next generation solution for power system control and monitoring. The new design is based on the use of synchronized sampling technology and multifunctional Intelligent Electronic Designs (IEDs). The advantages of such systems are discussed pointing out new benefits to be gained by different users.. The new solution enables full use of field recorded IED data by various utility groups such as protection engineers, dispatchers, maintenance crews, asset managers, and independent system operators. The deployment strategy and examples of initial steps are presented making reference to the specific on-going project aimed at field deployment of the solution.

1. Introduction

Digital substation technology has been first introduced in the early eighties [1]. Over the next couple of decades the technology has evolved from individual Intelligent Electronic Device (IEDs) designs to implementation of integrated Substation Automation Systems (SASs) [2]. The next step was to introduce all digital instrument transducers that can be directly interfaced to a serial high speed process bus in substations [3]. Most recently, the substation IEDs are being designed to offer quite versatile recording and monitoring functions in addition to traditional applications [4]. Last, but not least, all the substation IEDs are now being designed with an interface to the reference time signal provided by the Global Positioning System (GPS) of satellites for the synchronization of signal sampling and time stamping of recorded events.

The all-digital substation automation systems of the future will serve the needs of number of diverse utility personnel, namely protection engineers, dispatchers, maintenance crews, asset managers, and independent system operators. This new approach in designing control and monitoring systems has two distinct features that make them different from the existing legacy designs [5]: a) the data collected by IEDs will be automatically processed at the substation and other hierarchical levels in the information processing utility infrastructure, and b) the extracted information will be shared by the different utility groups allowing them to have better view of the system.

The paper first gives a brief discussion of the background technology to be used in the future solutions. The issues of particular interests are the synchronized sampling and automated data processing [6]. It is pointed out that GPS-enabled IEDs are becoming readily available and automated data processing software is also emerging. A concept of the transparent substation processing in which the information users do not need to know where the field data is coming from as long as they get the best possible information about the events of interest is introduced and elaborated on [7].

The next issue of interest is the design approach for implementing future generation of the monitoring and control systems. This discussion identifies the major building blocks of such solutions. While most of the hardware needed for future systems is already available, some customized hardware may still have to be developed [8]. The rest of the needed developments is primarily in the software area where a number of modules for automated processing and analysis of different data and events respectively need to be made available.

An important consideration in promoting future generation of monitoring and control systems is the discussion of the benefits expected from such designs. Two distinct benefits are particularly important: a) better information, and c) more redundant data. Combining these benefits with the ability to extract information automatically leads to the monitoring and control capabilities that are faster and more robust.

The final consideration is related to the deployment strategies for future penetration of the new system designs. The specific deployment strategy presently undertaken in several on-going projects are reviewed and discussed.

2. Background Technology

The technology of interest comprises the time synchronization of the signal conditioning circuitry using referent signals from GPS receivers, advanced optical instrument transducers, multifunctional IEDs, and various communication media. Each of the technologies is briefly discussed next in the context of the future monitoring and control applications.

2.1. GPS-based Synchronized Sampling

The use of the Global Positioning System (GPS) of satellites is well known for the navigation purposes. In the utility industry this system is used for providing a reference time signal, which in turn can be received at each substation through a GPS receiver and then used for two purposes: a) synchronization of the sampling clock on the input data acquisition systems in IEDs, and b) time-stamping of the data acquired by IEDs. Those uses are illustrated in figure 1 given below.

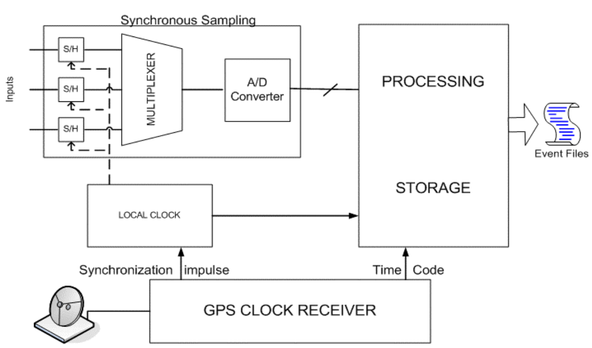

Fig.1. Synchronized sampling implementation

2.2. Optical instrument transducers

While not widely deployed yet, optical transformers are readily available for commercial use. The main advantages are the wide frequency bandwidth and high accuracy. In the commercial offering, they come with variety of outputs such as low and high power analog, as well as digital. The IEDs, connected to the new optical transducers need to have a matching input interface. The advantages of using this technology go beyond just the individual performance characteristics since the new transformers are allowing monitoring and control to be implemented with two very important application features: a) Single transducer may serve different types of IEDs (protection, monitoring, control), and b) single transducer may serve large number of IEDs via digital (process) bus. Last but not least, such transducers also need GPS synchronization of the output samples being placed on the digital (process) bus, as illustrated in figure 2.

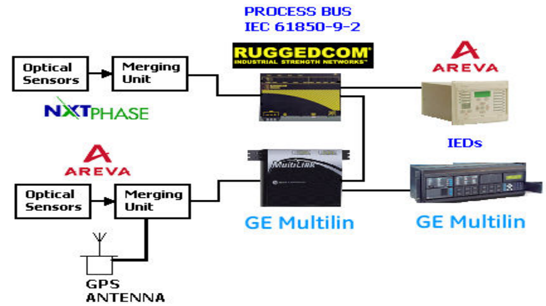

Fig.2. Typical optical transformer configurations

2.3. Communication media

Modern power system grid will have a number of options when it comes to communication media:

- Microwave radio
- Spread spectrum wireless radio
- Fiber optic cables
- High speed digital (process) buses

The main point about the communication media is the need to integrate different types into a hybrid communication system. While some of the interfaces are readily available, some are not. An earlier paper illustrates a novel hybrid system that integrated fiber optics media with high speed digital (process) bus [9].

2.4. Multifunctional IEDs

Digital (computer based) protective relays, recorders and controllers collectively called Intelligent Electronic Devices (IEDs) were introduced in the early 80-ties and have been used very successfully ever since. The advantages of such devices are numerous, but the most important are their ability to communicate through computer networks and the ability to host multiple, quite often unrelated applications. Both features are very important for future development of a modern grid monitoring and control system since the flexibility in the allocation of applications is significantly facilitated by multifunctional IEDs. One of the most interesting features is to have an IED that is GPS enabled and performs, besides its native function, a data acquisition function for monitoring purposes as well. In that case each IED can perform a dual function: a) customized function, and b) generic measurement functions.

The new dual role of multifunctional IEDs is now making it possible to even eliminate the classical Remote Terminal Units (RTUs) of Supervisory Control and Data Acquisition (SCADA) system.

3. Design and Implementation Issues

The design and implementation issues have huge impact on the development and deployment of the new monitoring and control systems. Addition of new hardware and seamless integration of modular software are considered key elements of the future solutions

3.1. Hardware and software design

The main expected trend is to have the IED hardware located closer to the source of information and related sensors, and have the software designed in a modular architecture so that the applications can be freely allocated across the overall information processing structure.

3.1.1. Hardware design. Most of the needed hardware exists in a form of multifunctional IEDs. The trend of developing hardware that will be placed directly next to the power apparatus or even embedded within the power apparatus such as breakers, instrument transformers, power transformers, etc is a visible trend for future development.

Another trend is to have the distributed hardware or embedded sensor systems networked in the switchyard, between the switchyard and control house in a substation, and across different substations and control center. This introduces a concept of a process bus that is linking all the sensors within s substation, as well as the information bus that is linking the outputs of all the IEDs within and across substations and control centers. Perhaps the future technology will enable linking of the process bus not only within the substation but also across all the substations. The features of the proposed future hardware design and illustrated in figure 3.

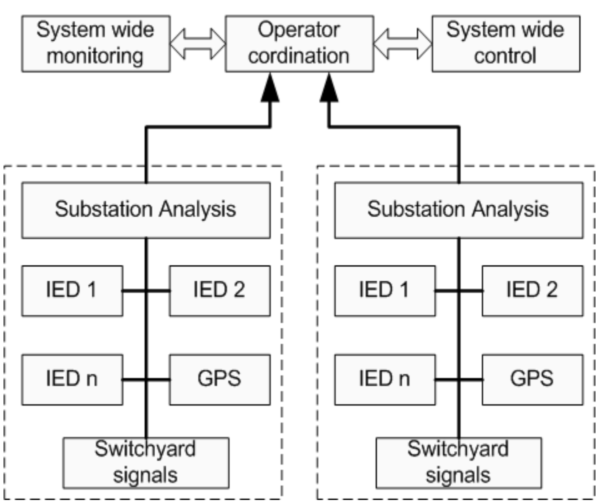

Fig.3. Future hardware architecture

3.1.2. Software design. Software design requires examination of many issues such as programming languages and implementation environments, database design, and modularity of application software.

Programming language and implementation environments are a very important part of the future development of monitoring and control systems. The programming languages that are used need to support the required transparency across operating systems and computational platforms since a variety of different computing resources will be deployed in substations and control centers ranging from laptops, desktop PC and high performance mainframes. The use of JAVA programming language and flexible operating systems such as Linux is a desirable approach.

Database design needs to support SQL functions and real-time features. Future power system applications will require a number of databases to be deployed and maintained across the system. To facilitate the access and understanding of the meaning of such data, tools for data modeling and data format representation will have to be flexible and widely understood. The solutions such as the unified modeling language (UML) and extensible mark-up language (XML) are the choices in that direction [10, 11].

Application software modularity is probably the most important design issue. Since the industry has huge suite of legacy applications already deployed, the modularity has to cater to the need for gradual upgrades and upward compatibility. Figure 4 shows the concept of different applications fitting together. The names of applications that are abbreviated in the figure will be discussed next.

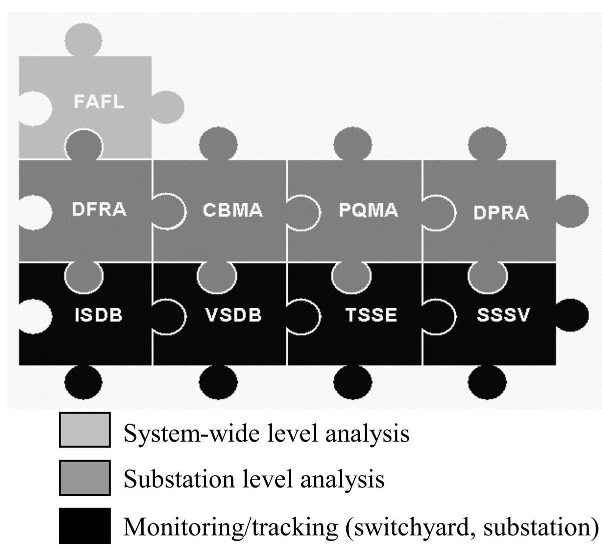

Fig.4. Future application software architecture

3.2. Implementation Strategy

This section outlines the major building block of the new monitoring and control system. The discussion focuses on two aspects: substation applications and centralized applications.

3.2.1. Substation Applications. Figure 4 illustrates the strategy how to enhance future solution of the monitoring and control system with several new applications. The applications are shown in more detail in a diagram depicted in figure 5.

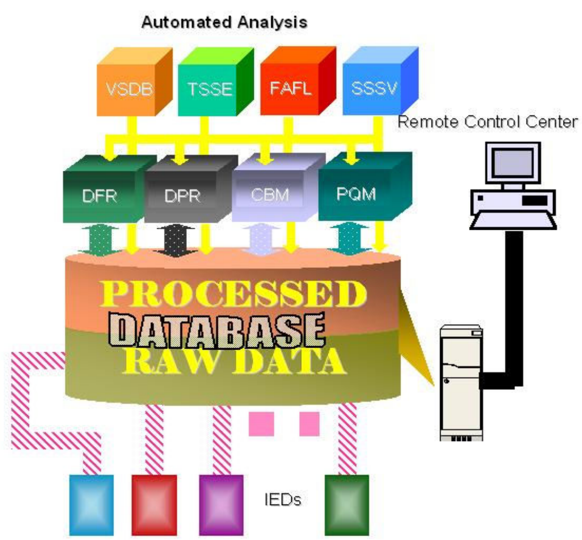

Fig.5. Future Substation Automation Solution

Two distinct features are important to note: preprocessing of raw data and data integration. This allows all the substation data to be made transparent to the new application functions.

New application functions fall into two categories. The first category is shown in the lower row above the database and relates to: automated analysis of data coming from substation IEDs such as Digital Fault Recorders (DFRs), Digital Protective Relays (DPRs), Circuit Breaker Monitors (CBMs), Power Quality Meters (PQMs), etc. The second category shown in the upper row serves multiple purposes: Verification of the Substation Database (VSDB), Two-Stage State Estimation (TSSE), Fault Analysis and Fault Location (FAFL), and Substation Switching Sequences Verification (SSSV). Between the two categories, the substation data is analyzed for variety of needs, some related to individual tasks of interest to various utility groups and some for automated analysis of events and disturbances.

3.2.2. Centralized Applications. Due to the processing performed at substations, the centralized solution will now look different than in the traditional EMS systems. The conceptual representation is shown in figure 6. Two distinct differences of the new solution should be noted: a) the substation data and extracted information are shared with different utility groups: protection engineers, dispatchers, maintenance technicians, etc, and b) each group receives the best information since the origin of substation data becomes transparent to the users. Those two improvement create the highest benefit since the overall data is quite robust due to the additional redundancy and cause-effect correlations that are now feasible to implement.

The most relevant improvement in this new concept is the ability to deploy multiple data processing functions at the substation level using substation computer that can host the applications and database. As may be observed from the description of figure 6, the applications also perform preprocessing of data so that the relevant information for each of the user groups is extracted and sent to the centralized location. Two advantages of such an approach should be noted. First, the information, not data, is sent from substations to the upper levels for the operators to be able to use it in real-time. The information is extracted from the data in the time frame allowing real-time use. This prevents the communication bottleneck. The raw data, if needed, is sent at a later time when the traffic is not so frequent. Second, the local information is extracted close to the source using abundance of data coming from IEDs. If a coordination of local conclusions is needed, this can be accomplished through further exchange of information.

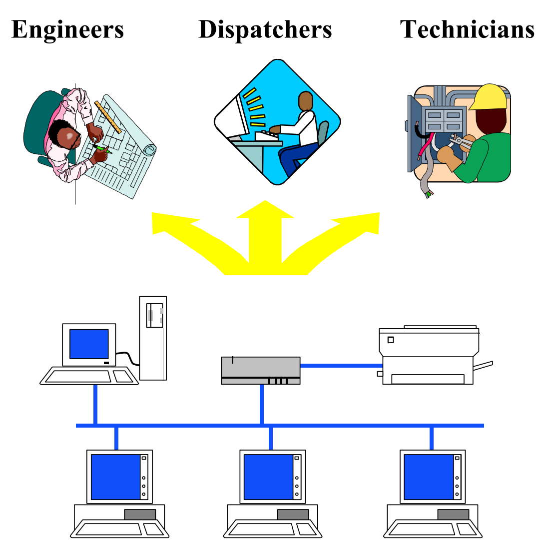

Fig.6. Future Centralized Solution

4. Examples of Deployment Projects

The proposed overall concept has been under development for some time. Different applications as building block have been implemented and some already deployed, while some others are planned for deployment in the future. Each of the on-going deployment activates are discussed next.

4.1. Selection of a field demonstration site

The first step in the deployment was to select a substation site where the outcomes of various projects could be deployed. The selected substation one line diagram is shown in figure 7.

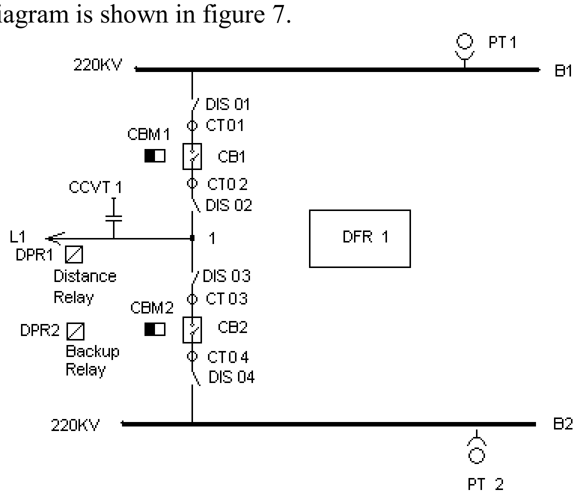

Fig.7. One line diagram of a portion of a substation

From the diagram it can be observed that a transmission line of interest has two breakers associated with it. Each breaker is equipped with a Circuit Breaker Monitor (CBM) developed in a separate project, and to be discussed in the subsequent sections related to deployment. The transmission line is protected with two relays; the primary and back up. Each Digital Protective Relay (DPR) is of a different type, and that is usually the practice in the utilities. Besides CBMs and DPRs, the substation is equipped with a Digital Fault Recorder (DFR), which records data from all the transmission lines including the one shown on the diagram.

The data collected by the shown IEDs includes:

- Currents and voltages from instrument transformers
- "a" and "b" contacts from circuit breakers
- Trip signals from relays
- Relay communication scheme signals
- Additional contacts from the control circuitry of the breakers

4.2. Automation of substation data processing

A project aimed at automating processing of data from Digital Fault Recorders DFRs), Digital Protective Relays (DPRs), and Circuit Breaker Monitors (CBMs) is a reduced version (subset) of the general substation automation development specified in figure 5. The architecture of this development has two important components: substation connections of IEDs to GPS receiver, and development of the software for automated data analysis. The connections of specific equipment in a substation are shown in figure 8 and the client/server architecture of the software solution is shown in figure 9.

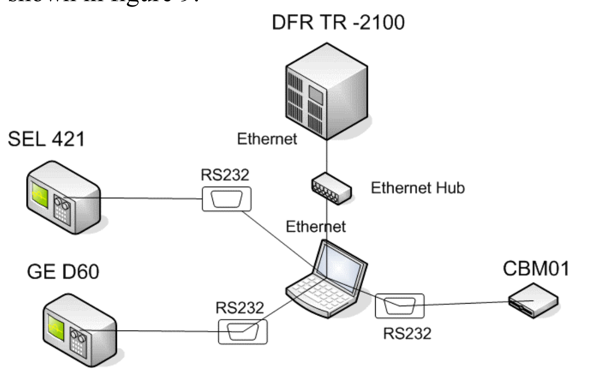

Fig.8. Connections of IEDs in a substations

What may be noted from figure 9 is that the synchronized sampling technology, discussed earlier as the main building block and shown in figure 1 is actually deployed in this effort. As noted, the software deployment represents a reduced version of the general development suggested in figures 5 and 6, where the only reduction is in the number and type of IEDs used.

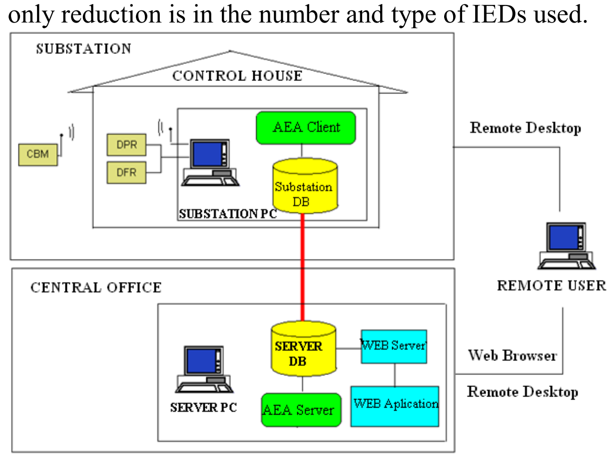

Fig.9. Software architecture for substation automation

4.3. Circuit breaker and topology monitoring

This project is aimed at developing a new circuit breaker monitor (CBM) that has an ability of automatically tracking the state of the breaker in real time. In addition, this development covers monitoring of CB switching sequences in real time with GPS accuracy and time stamping. Further description of both development projects is given next.

4.3.1. Automated circuit breaker monitoring. This development has been focused on monitoring of the control circuit signals that reflect the operating state and performance of the switching action of a circuit breaker [8]. Typical signals that are monitored are shown in Table I.

Table I. Control signals monitored by CBM

Signal Name
Control DC
Yard DC
a Contact
b Contact
Trip Current 1
Trip Current 2
Close Current
Trip Initiate
Close Initiate
X Coil
Y Coil
Phase A Current
Phase B Current
Phase C Current

The architecture of the CBM deployment for single CB is shown in figure 10. The main components of the software are a signal processing routine aimed at the feature extraction and expert system part aimed at the reasoning process. The CBM unit is located in the switchyard at the breaker cabinet and communicates with a PC located in substation control house through a spread spectrum wireless link.

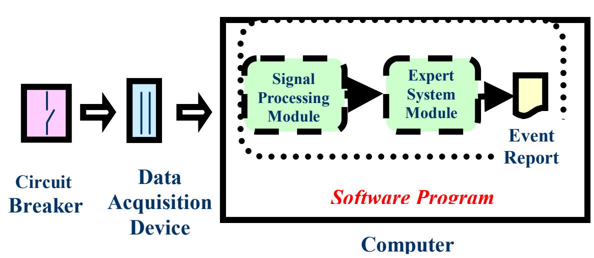

Fig.10. CBM hardware and software

If one places several CBM in the field, they are than capable of monitoring with the same level of detail a sequence of CB operations. Figure 11 shows an architecture of such a configuration deployed in the field.

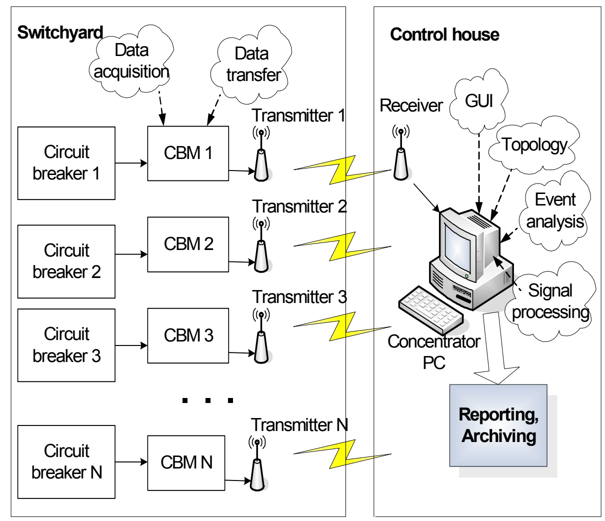

Fig.11. Monitoring of a sequence of CB operations

The main advantage of this approach is the ability to monitor operation of any single breaker and its sequence as well as operation of several circuit breakers in a sequence, which leads to an ability to monitor the switching state of all the breakers in a substation, and ultimately in the overall system. With this technology, the changes in the topology can be tracked with GPS precision and time stamping. Figure 12 shows a time sequence monitoring of an operation of two breakers aimed at clearing a fault on the line connected through two breakers, shown in figure 7.

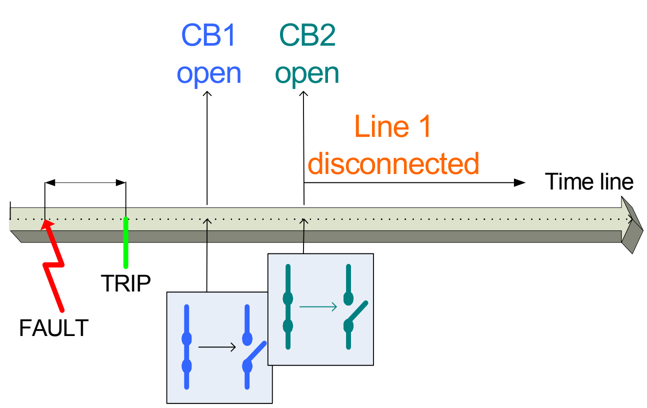

Fig.12. Time-sequence analysis of a group of CB

5. Conclusions

The main observations related to the future monitoring and control systems may be summarized as follows:

- Synchronized sampling technology and multifunctional IEDs represent major elements of the new designs
- Availability of new customized IEDs and modular software solutions in necessary for flexible implementations
- Deployment strategies need to be step-wise allowing for gradual transition from existing legacy systems to new solutions
- The proposed design of the monitoring and control system will benefits multiple utility groups: protection, maintenance and asset management, and operations.

6. References

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7. Acknowledgments

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8. Biography

Mladen Kezunovic (S'77–M'80–SM'85–F'99) received the Dipl. Ing., M.Sc. and Ph.D. degrees in electrical engineering in 1974, 1977 and 1980, respectively. Currently, he is the Eugene E. Webb Professor and Director of Electric Power and Power Electronics Institute at Texas A&M University, College Station. He was with Westinghouse Electric Corporation, Pittsburgh, PA, and the Energoinvest Company, Sarajevo, Bosnia-Herzegovina. He was also with the University of Sarajevo, Bosnia-Herzegovina, and a Visiting Associate Professor at Washington State University, Pullman, from 1986 to 1987. His main research interests are digital simulators and simulation methods for relay testing as well as application of intelligent methods to power system monitoring, control, and protection. Dr. Kezunovic is also a Fellow of IEEE and a member of CIGRE.