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The 21st century substation design: Vision of the Future

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Abstract

This paper discusses the 21st century substation design requirements, which should meet the following criteria: improved reliability, cost, interoperability, re-configurability, security, controllability and flexibility. Such criteria require designs that use new methodologies quite different from the existing philosophy. The design strategies are focused on reducing cost while maintaining the performance, or maintaining cost while improving performance. Based on the considerations mentioned above, we proposed three design approaches: a) retrofitting the existing substations by replacing legacy equipment with new technologies without disrupting continuity of service, b) implementing brand new substation design using of-the-shelf technologies, and c) envisioning green-filed substation design considering energy market, profit optimization and system-operation/price.

***Index Terms*—Future Substation Design, Design Criteria, Retrofit, IEDs, Substation Automation,**

Introduction

Many of the US substations are now more than thirty to fifty years old and soon in need of upgrade or replacement. The US National Institute of Standards and Technology (NIST) has recently published their smart grid framework release 1.0 document [1], which was in response to the Energy Independence Security Act (EISA) of 2007 and American Recovery and Reinvestment Act (ARRA) of 2009. A review of these documents indicates a need to develop smart substations in the future.

The future substation design requires an understanding how both primary and secondary equipment may interact in the substation, how primary system parameters may be converted to secondary quantities by using multifunctional intelligent electronic devices (IEDs), and how the availability of new types of signal sensors may eliminate many of the drawbacks related to conventional instrument transformers. This paper is mainly focused on the secondary side design.

Lot of investigations in the past concentrated on creating a concept of the future substation based on new technologies that would increase capacity, and reliability, while reducing the cost of maintenance as well as addressing the reduction in size, increase in data processing speed and proliferation of automation [2-7].

The publication of IEC 61850, the new international standard for substation communications, is an extremely important step in the definition of the "copper-less" substation of the future and will have the greatest impact on future substation design. Intelligent electronic devices (IEDs) being implemented in substations today contain valuable information, both operational and nonoperational, needed by many user groups within the utility. Recent development in the standards for substation automation integration is allowing interconnection among IEDs available in modern substations into one system [8]. As a result, a variety of new applications that utilize overall substation data may be envisioned [9]. Distributed substation applications based on high-speed peer-to-peer communications of change of state of breakers, protection and control functional outcomes or current and voltage sampled values will lead to very efficient and at the same time functionally superior substation solutions.

The paper discusses the new design criteria, new technologies, and new design approaches and draws conclusions about expected benefits.

New Design Criteria

For the substation development to reach its technical and economical potentials, the focus has moved now to studying how substations may enable more intelligence in the network, which is labeled the “smart grid” development. It has been concluded that the 21st century substation design should meet the following improved criteria: reliability, security, interoperability, re-configurability, controllability, maintainability, flexibility, reduced cost and environmental impact [10]. An estimate of the importance of the different criteria is shown in Fig. 1. The four major criteria commonly emphasized by substation designers are reliability, cost, operational flexibility and environment impact.

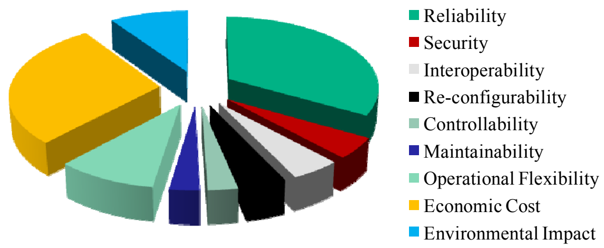

Fig. 1. The different criteria for the 21st century substation design

Future substation designs will be driven by new technologies and standards, as well as some new methodologies which are quite different from the existing philosophy. The design requirements will be aimed at either the cost reduction while maintaining the same technical performance or the performance improvement while assuring no or minimal cost increase. Based on the considerations mentioned above, three possible design approaches may be studied: a) retrofitting the existing substations with a major replacement of the legacy equipment while maintaining minimal disruption to the continuity of the services, b) deploying brand new substation design using latest of-the-shelf technologies, and c) envisioning green-field substation design which takes energy market participation and profit optimization into combined consideration.

New Technology Landscape

A. Available technologies

Major new technology used in the new substation comprises the GPS-based synchronized sampling, optical sensors, diverse communication media and multifunctional IEDs.

1) Synchronized sampling

The utility industry uses Global Positioning System (GPS) of satellites for providing a reference time signal, which in turn may be received at each substation through GPS receiver. There are two purposes for using the time signals

- Synchronizing the sampling clock at the input of data acquisition systems in IEDs.
- Time-stamping the data acquired by IEDs.

2) Optical current and voltage sensors

The main purposes for optical sensors are the wide frequency bandwidth, wide dynamic range and high accuracy. Furthermore, the new sensors allow monitoring and control to be implemented with two important application features: Single sensor may serve different types of IEDs; Single sensor may serve large number of IEDs via process bus.

3) Communication media

Modern substation will have a number of options when it comes to inter- and intra- communication media: Microwave radio, Spread spectrum wireless radio, Fiber optic cables, and high speed coaxial cable serial bus.

The two options for optical fiber uses are: single mode and multimode. Single mode may have one stream of laser-generated light used for long distance communication, where multimode has multiple streams of LED-generated light used for short distance communication. Several benefits of optical fiber can be identified: support long distance telecommunication, greater capacity, smaller size, lighter weight, and electromagnetic isolation. In the proposed new substation design, a hybrid system that integrates fiber optic cables with high speed process bus concept is adopted.

4) Multifunctional IEDs

Multifunctional IEDs integrate more functionality into fewer devices, resulting in simpler designs with reduced wiring. The most important advantages of IEDs are communicating through computer networks and hosting multiple applications, so more information could be made available remotely. For the modern grid monitoring and control system, we need GPS enabled IEDs which perform, besides its core function, an elaborate data acquisition function for extensive monitoring purposes as well.

B. Future technologies

1) Multiplexed sensors

The Fabry-Perot interferometer (FPI), also called the Fabry-Perot etalon, consists of two mirrors of reflectance R1 and R2 separated by a cavity of length L [3].

Benefits of the FFPI over conventional sensing technologies for instrumentation of the electric power grid include [3]:

- Immunity to electromagnetic interference, reduced susceptibility to lightning damage, and freedom from grounding problems, which affect other sensors in the presence of high electrical currents and voltages;
- The ability to locate electronic equipment used in sensor monitoring and signal processing at remote distances from the sensing elements themselves;
- High sensitivity to a variety of measurands;
- The ability to multiplex many sensors to diverse types over a single optical fiber lead connection;
- Small size and light weight for the sensing elements;

- The potential for reduced life-cycle cost of instrumenting the electrical power grid.

Multiplexing is defined as the use of one optical source to supply light to multiple sensors, the use of one photodetector to convert the optical signal from multiple sensors, and the use of one electronic signal processor to compute measurand values for multiple sensors. Multiplexing reduces the cost per sensor. Its application is essential to cost-effective instrumentation of substations, where many points are to be remotely monitored. Architecture of the multiplexed sensor network, together with an associated Signal Conditioning Unit (SCU) is shown in Fig. 2.

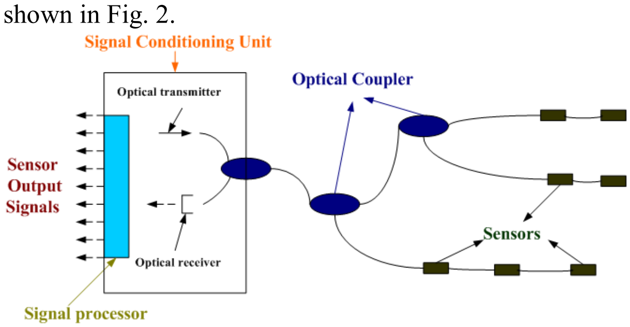

Fig.2. Multiplexing arrangement for FFPI sensors

2) Advanced Alarm Processing
The proposed alarm processoring approach includes two modules, one at the substation and one at the system level respectively [11]. A two-level structure is introduced to effectively use the enormous amount of data available at the substation automation system (SAS) level. The local processing at the computers in substations is carried out and the results of such analysis are transmitted to assist the energy management system (EMS) level alarm processor. Fig.3 shows the overall software structure as used to demonstrate the proposed concept
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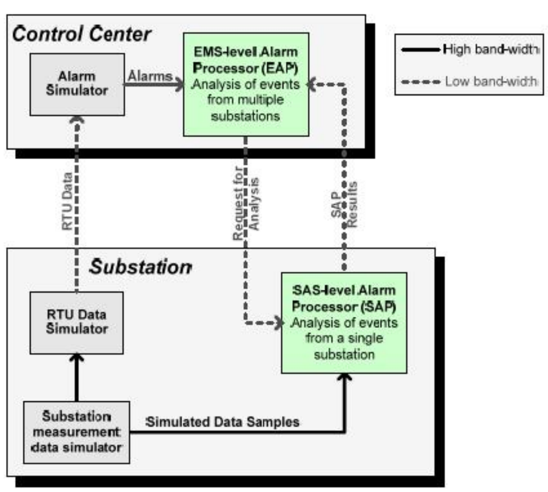


Fig.3. Overall Software Structure

This design has several benefits:
- The SAS-level alarm processor uses measurement data that are only available within the substation and therefore is more capable of recognizing the nature of disturbance in the substation.
- The EMS-level alarm processor relies largely on the results of SAS level alarm processor. Since most of the analysis work has been done separately at the substation level, the EMS-level alarm processor is very efficient.

Due to the two-level structure of the proposed alarm processor, more complex analysis functions can be accomplished in a reasonable time. The dispatchers are prompted with more useful and distilled information, including suggested actions to be taken.

Retrofit of existing substation

This section discusses how to retrofit the substation secondary equipment with information technology to meet some new requirements.

A. Limitations of Existing Substation

The average age of existing substation is more than forty years old. Although there are some maintenance planning and repair strategies that can prolong the life time of anold substations, the high cost of operation, maintenance and service with negative impacts on reliability forces the utilities to upgrade their old substations.

B. Future needs

The main concern of a retrofit is to take into account legacy equipment and the need to have minimal disruption to the continuity of services. To reach those goals, a comprehensive survey of new technologies has to be done and the cost benefit analysis should be addressed.

C. Proposed retrofit strategies

Our retrofit strategy is split into two scenarios that will be discussed in details:
- Extensive use of new IED technologies in the existing substation;
- Extensive use of fiber optic cables;

Extensive use of new IED technologies

The secondary equipment of the substations can be divided into two different concepts: either mount the data acquisition in the yard to collect data from primary equipment called switchyard monitoring devices or installed in the control house to perform data acquisition and processing such as found in protective relays.

1) Switchyard data acquisition devices
The main functionality of these devices is to collect data from primary equipment at the substation yard next to transformers, circuit breakers, power lines, etc. Such devices are developed by most of the major companies such as Siemens, ABB, GE, SEL, Syprotec, Ningbo Tech, Monitoring Device Company, etc [12]-[19]. Original copper-wired analog instrumentation for data transfer may be replaced by optical instrumentation with fiber-based sensors for monitoring and metering. The most prominent advantages are high accuracy, no saturation, reduced size and weight, safe and environmental friendly (avoid oil or SF6), higher performance, wide dynamic range, high bandwidth and low maintenance [12]-[19], as shown in Fig.4.

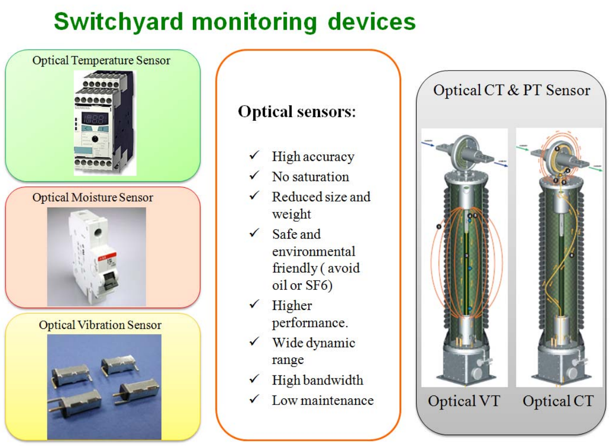


Fig. 4. Switchyard monitoring devices

2) Multifunctional Intelligent Electronic Devices (IEDs)
As an illustration of the concept, protective relays are widely used in substations for different purposes. While they are primarily used to achieve individual functions, such as differential protection, distance protection, over-current protection, metering, monitoring and etc. they are also utilized to perform several monitoring, control and user interfacing functions in one box. The main advantages of multifunctional IEDs are: fully IEC 61850 complaint, compact size, various functions together in one design. This means reduction in size, increase in computational efficiency and improvement in robustness.

Extensive use of fiber optic cables

In a large substation, the cable length is around 200000 feet (17000 feet 12/C cable). The weight of copper wiring is pretty high, and this creates issues when pulling in new wiring. In the old substations, the wiring cables have been damaged substantially by rodents. Also, the electrical substation environment has many environmental challenges to overcome in providing reliable and secure communications. Such challenges involve high voltages, extreme temperature, high fault currents, electromagnetic interfaces, and electrostatic discharge. The best option for upgrading the communication wiring of this kind of substations is fiber optic [20]. The reliability, performance and weight of this wiring material can affect the entire performance of the substation. The other advantages of this technology are higher communication speed, longer distance of transmitting information, greater resistance to electromagnetic interferences and lower cost. Both technical and cost considerations have to be taken into account in the decision to replace the damaged copper cables with fiber-optic cables. Installation of fiber optic is pretty difficult and it requires expert human resources. Also, fiber is sensitive to twists and microbands. These shortcomings should be considered when making retrofit strategy decisions.

The fiber-optic cable is connected to each primary power apparatus such as circuit breakers, transformers, reactors, etc through a data acquisition unit. Each primary equipment measurements can be multiplexed together and only one fiber-optic cable may be used to bring all the measurements to the control house. This approach saves considerable amount of wiring as the distance between the primary apparatus and control house is on average around 1000 feet [19]. Using fiber-optics in the proposed retrofit design minimizes the wiring requirement saves considerable amount of money.

New Substation Design

In the legacy substation, the interface between switchyard and control house is hard-wire connected. A combination of rigid wiring and low speed digital communication bus is used for exchange of information between IEDs. In order to realize sophisticated IED control schemes requiring inter-IED interaction, a large number of interconnections between multiple IEDs are required [21]. Since low-speed serial communications is often limited to master/slave communication, peer-to-peer communications between IEDs is needed to meet the communications requirements.

The new substation design adopts synchronized sampling technology and multifunctional IEDs as the key aspect of the design [22]. The data from different IEDs in that case is automatically processed at the substation, and related information is extracted so different utility groups can get the information of interest The new design realizes the integration of data and required signal processing across the substation. This section gives further details of this new concept

A. New Control, monitoring and protection design

The architecture which illustrates “fusion” between power apparatus and infrastructure for monitoring, control and protection, is shown in Fig.5.

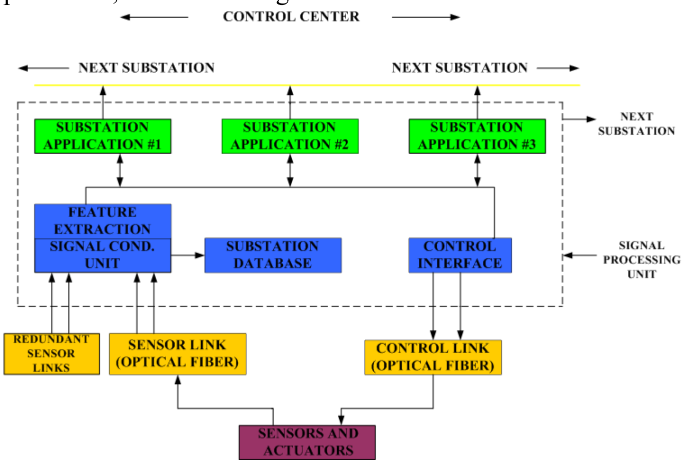


Fig. 5. Architecture of new monitring and control network

This system uses multiplexed fiber optic cable to bring a variety of measurement sensors together on a single sensor link, which can be repeated as many times as needed to provide redundancy. Then the links are interfaced to an analog-to-digital conversion system (Signal Conditioning Unit), which converts all the measurements into a common substation database. Combined with synchronized sampling at the conversion unit, all the measurements may be time stamped using Global Positioning System (GPS) reference time signal. After that, the samples of substation measurements are available to a signal processing unit (Feature Extraction), which feeds a variety of substation applications with extracted features such as samples, phasors, and frequency using any combination of processing units as needed. All the processing units are connected to a wide-area communication network that allows exchange of information or data across any number of the substations if is necessary. The control center applications are also connected to the same wide-area communication network, allowing access to all the substations and individual processing elements within substations. The actuators take actions according to the control signal communicated through the control link (Optical fiber).

B. New Substation Design

Fig.6 shows a version of the new design implemented using off-the-shelf components [23]. The new system has two distinct features different from the legacy designs:

- The data collected by IEDs is automatically processed at the substation and other hierarchical levels of information processing in utility infrastructure;
- The extracted information is shared by the different utility groups allowing them to have better view of the system.

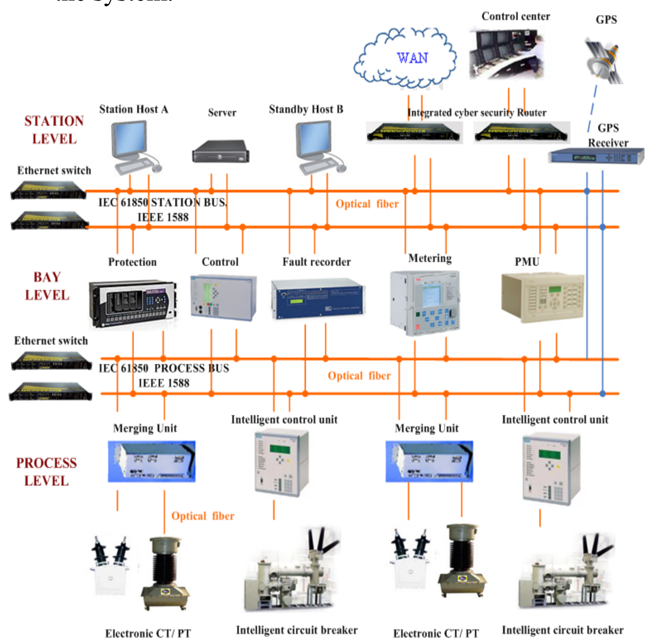


Fig. 6. Proposed Susbstation Diagram

Synchronized sampling technology and multifunctional IEDs represent major elements of the new designs. The multiplexed fiber sensor and control network in the new design allows an easy integration of substation data. The new design makes the data transparent, so the substation and control center applications can access data in the same manner, so the new design will benefits multiple utility groups: protection, maintenance and asset management, and operations.

Green Field Substation Design

The advent of electricity market deregulation has placed great emphasis on the availability of information, the analysis of this information, and the subsequent decision –making to optimize system operation in a competitive environment. This creates a need for better ways of correlating the market activity with the physical system states in real time and sharing such information among market participants. Future “intelligent” substations should play an important role in the overall “Smart Grid” and be capable of providing such information.

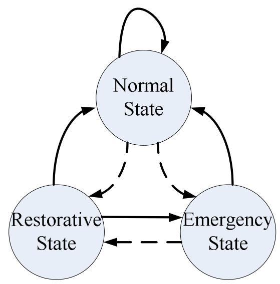
Since the power system events effects not only the operation of the power system, but also the power market, it can be conjectured that the importance of an electric event should be expressed in terms of the economic importance, and the economic impact should be correlated with electrical alarms [24]. Therefore, it is proposed that alarm issuance and alarm processing should include economic information in addition to the contemporary alarms.

In this section, an Intelligent Economic Alarm Processor (IEAP) architecture to bring the electricity market function into the future substation design is proposed. The basic concept is to link the electricity market operation with real-time monitoring of the physical grid providing market participants and operators with economic information associated with trends in the physical system. Dr. Stahlht and Dr. Heydt first raised the idea of “economic alarms” in their work [24]. They ranked the alarms based on the economic severity. In their approach, a set of predetermined events that would give certain suppliers the ability to exercise market power will trigger an alarm. The new alarm processor proposed in this paper further extends that idea. It first gives a list of the fault occurrence possibility based on the SCADA/IED signals received. Following these events, changes in power flows, LMPs and other economic indices is calculated and analyzed. A closer cause-effect relationship between the physical power system and the market is provided. Both physical and economic alarms are translated into easy-to-understand information to operators and market participants.

A. Basic assumptions

The market structure for buying, selling and scheduling electricity includes forward bilateral contracts as well as centrally coordinated markets for day ahead, hour ahead and real time energy and ancillary services. Once the forward markets have closed, the real time market operation coincides with real time system operations. Schedules from the forward markets are implemented in the real time dispatch and resources made available through the markets to provide ancillary services are selected and dispatched by the system operator for balancing (or load following) and regulation. In our example the locational marginal prices (LMPs) from the real time market are used for financial settlements of the real time dispatch and transactions.

When some operating parameter, such as voltage, exceeds acceptable threshold, the system shifts spontaneously (dotted line in Fig 7) to an unstable “Emergency” state. The result is usually an automatic control action (solid line), such as the tripping of a relay, which takes the system into a more stable but not fully functional “Restorative” state. Analogous states and transitions are also applicable in power markets, with some notable differences, as shown in Fig.7.



Type	Configuration	Market Parameters
Normal	All MPs Complete	Within limits
Emergency	All MPs Complete	One or more parameters violate the limits
Restorative	Structure incomplete	Within limits

*MPs (Market Participants) include generator companies, transmission owners, load serving entities and other nonasset owners such as energy traders.

Fig. 7. Grid and Market operating states

If system reliability is not immediately threatened, the Intelligent Economic Alarm Processor, proposed below, would give market participants advanced notice of an imminent need to find additional resources to serve scheduled loads, find replacement transmission transfer capability, or meet ancillary services needs. Marketers may often be able to find economic resources more readily than the system operator if they are given advanced notice.

B. Features of the Proposed Intelligent Economic Alarm Processor

The overall architecture of the proposed IEAP model is shown in Fig.8.

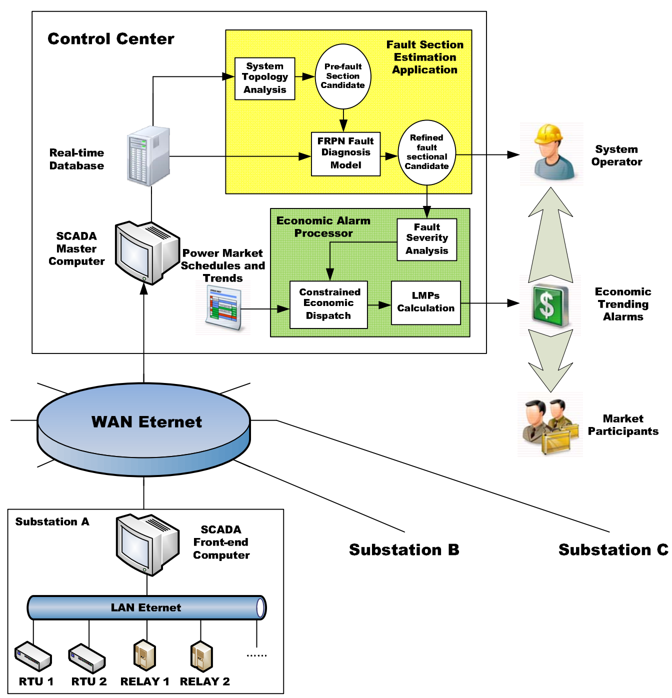


Fig. 8. Intelligent Economic Alarm Processor Architecture

An example of a detailed mathematic model is discussed in [24]. Ideally, the economic trending module will yield the following information:

- Cause-effect relationship of the fault

- Anomalous changes in the LMPs;
- Trigger alarms based on volumes;
- Identification of predicated limitations of available transmission capability (ATC) that is problematic;
- Identification of energy needs as a consequence of planned events;
- Predicated high reactive power demands.

This proposed economic alarm processor would send signals changes including the LMPs, congestions, shadow prices etc. to all the market participants, which allow them to know information on a variety of levels:

- To access the short term transmission needs in the system
- To allow for operators to redispatch generators based on scheduled transactions and real time market needs
- To make the power market more transparent, providing information to all
- To assist in making transmission operating decisions optimal for economic efficiency as well as for system reliability.
- To allow market participants to identify trends in LMP, line loading and demand levels in order to find/make transactions in the near future in anticipation of these trends.

Conclusion

Technology and standards are continuously being developed and drive the ability to improve performance and quality of substation designs. New technologies for digital communication systems, intelligent electronic devices and visualization systems, as well as computing capabilities embedded in the power apparatus are entering the substation design practice.

Based on the design approaches and related evaluation studies discussed in this paper, several conclusions may be drawn:

- Retrofitting existing substations is not easy due to the legacy wiring and equipment interfacing constraints. However, data integration and information exchange may be facilitated by new software solutions that can be easily added to the existing substation design
- Designing new substations allows for more flexibility since equipment interfaces and switchyard wiring may be done in several different ways that facilitate better utilization of the multiplexed sensors and multifunctional IEDs
- Envisioning green field design leads to an idea that merging the electricity market data with the grid operational data captured through distributed substation intelligent economic alarm processor may offer some benefits in the future operation of both the market and electricity grid

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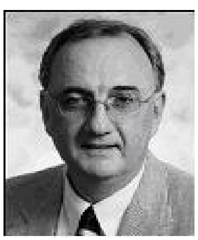
Biographies



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