Communication Infrastructure for Emerging Transmission-Level Smart Grid Applications

Y. Dong, *Student Member, IEEE*, and M. Kezunovic, *Fellow, IEEE*

***Abstract*—This paper investigates new applications in transmission system operation, protection and maintenance and discusses concerns in designing communication infrastructure to implement these applications. Requirements from such applications are highlighted by study of use cases. Standards associated with data format, communication protocols and cyber security are then identified. A generic communication infrastructure and problems in selection of communication technologies for the new applications are addressed at last.**

***Index Terms*—communication infrastructure, smart grid, transmission system, system operation, protection and maintenance**

I. Nomenclature

CBM	Circuit Breaker Monitoring
DHS	Department of Homeland Security
DPR	Digital Protective Relay
EMS	Energy Management System
EPRI	Electric Power Research Institute
FL	Fault Location
GIS	Geographic Information System
IED	Intelligent Electronic Device
LAN	Local Area Network
NASPI	North American SychroPhasor Initiative
NIST	National Institute of Standards and Technology
PMU	Phasor Measurement Unit
RCM	Reliability-centered Maintenance
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SGIP	Smart Grid Interoperability Panel
SPS	Special Protection Scheme
TM	Transformer Monitoring
WAC	Wide-Area Controller
WAMS	Wide Area Measurement System

This work was supported by Power Systems Engineering Research Center (PSerc). Project No: T-39.

Y. Dong and M. Kezunovic are with the Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843-3128, USA (e-mails: dongyimai@neo.tamu.edu; kezunov@ece.tamu.edu).

II. Introduction

THE term "Smart Grid" refers to a modernization of the electricity delivery system so it monitors, protects and automatically optimizes the operation of its interconnected elements – from the central and distributed generator through the high-voltage network and distribution system, to industrial users and building automation systems, to energy storage installations and to end-use consumers and their thermostats, electric vehicles, appliances and other household devices [1]. The US Department of Energy has defined seven characteristics of the smart grid:

- Enabling active participation by consumers;
- Accommodating all generation and storage options;
- Enabling new products, services, and markets;
- Providing the power quality for the range of needs in a digital economy;
- Optimizing asset utilization and operating efficiently;
- Anticipating and responding to system disturbances in a self-healing manner;
- Operating resiliently against physical and cyber attack and natural disasters.

Others, including Duke Energy's "Utility of the Future", EPRI's "Intelligrid", the GridWise Alliance, and the National Energy Technology Center's "Modern Grid Strategy" have set similar goals for the smart grid. These characteristics define a substantial step forward in the capabilities of the grid, and promise a more reliable, efficient, and secure grid to meet the coming challenges of electricity delivery.

All the characteristics defined by any vision of the smart grid share one common and critical need: communications. Not only does proper communication provides more information from the system and improves existing operation and management solutions, it also transmits data with higher quality and speed, from multiple locations of measurements, and serving multiple users, including new applications that are yet to be commercially implemented.

The study of smart grid communication has been initiated for quite some time by several organizations. The National Institute of Standards and Technology (NIST) has been working on coordinating development of a framework that includes protocols and model standards for information management to achieve interoperability of smart grid devices and systems. The Smart Grid Interoperability Panel (SGIP) was established by NIST to coordinate development of interoperability standards. In their report for Phase I of the NIST plan, “NIST Framework and Roadmap for Smart Grid Interoperability Standards”, a high-level conceptual reference model for the Smart Grid, existing standards that are applicable (or likely to be applicable) to the ongoing development of the Smart Grid, high-priority gaps and harmonization issues (in addition to cyber security) for which new or revised standards and requirements are needed, and the strategy to establish requirements and standards to help ensure Smart Grid cyber security have been addressed [2].

The Electric Power Research Institute (EPRI) assisted NIST in identifying issues and priorities for developing interoperability standards since 2009. To study the smart grid process definition and requirements development, a Use Case Repository has been built, which documented applications for customer service, distributed energy resources, distribution operations, federated system management functions, market operations and transmission operations [3].

In the study of communication architecture, the North American SychroPhasor Initiative (NASPI) has been developing an industrial grade, secure, standardized, distributed, and expandable data communications infrastructure to support synchrophasor applications in North America, called “NASPInet”. The NASPInet is envisioned as supporting a hierarchical flow of data and information from utilities, to regional reliability centers, and on to NERC (North American Electric Reliability Corporation) [4]. A basic conceptual architectural diagram of the NASPInet that includes PMUs, Phasor Gateways and the Data Bus is shown in Fig. 1.

It should be noticed that one of the important features of smart grid development is the ability of implementing new applications, while most of the studies are focusing on existing applications. For example, EPRI has documented 36 use cases for transmission operation applications, all of which already serve in system operation. The emerging new applications, on the other hand, are often ignored.

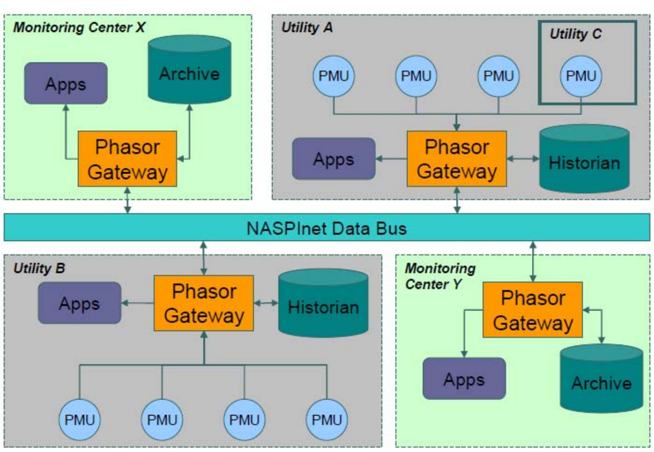

Fig. 1. Basic conceptual architectural diagram of the NASPInet [4].

Requirements from the new applications may differ from the existing ones in several ways: accuracy, latency of data transfer, bandwidth, etc. Communication infrastructures designed for the existing applications may fit for the new applications, but there is also possibility that retrofit or new design is needed.

The purpose of this paper is to address the challenges in communication associated with implementation of new transmission-level applications. Following problems will be discussed in the next sections:

- *The emerging applications that may benefit from smart grid development and the communication requirements:* what are emerging applications with new communication requirements?
- *Standardization needs:* whether existing standards cover what is required in smart grid communications*?*
- *Communication infrastructure:* are the existing infrastructures capable of meeting requirements brought by new applications?
- *Mapping methodologies:* what is to be considered when choosing communication infrastructure to serve a particular application/ a group of applications*?*

III. Emerging Transmission-Level Applications

Four applications have been chosen as samples from set of new transmission-level applications, covering areas of transmission operation, protection and maintenance. These applications are: intelligent alarm processing, automated fault location, cascading analysis and reliability-centered maintenance.

A. Description of New Applications

1) Intelligent Alarm Processing

Alarm processing serves system operators by performing alarm suppression, alarm prioritization, and reduction of alarms on the basis of cause-effect analysis. It assists power system operators in responding more efficiently to the stressed power system conditions [5]. It also provides data resource for optimized fault location and cascading event analysis. At system level, information that is required by different functional modules is extracted from field measurements according to the respective needs. At local level, it could be observed that the data required by this new alarm processor is a combination of SCADA measurements and measurements from other Intelligent Electronic Devices (IEDs), e.g. Digital Protective Relays (DPRs).

2) Automated Fault Location

The automated fault location method selects a suitable Fault Location (FL) algorithm from three types of algorithms: two-end FL algorithm based on synchronized samples, single-end or multiple end phasor based FL algorithm, and system-wide sparse measurement based FL algorithm. Details of this application are reported in [6]. The measurement equipment used is sparsely located Digital Fault Recorders (DFRs), Digital Protective Relays (DPRs) or other GPS-based IEDs, e.g. Phasor Measurement Units (PMUs) or digital protective relays. Commercial software like PSS/E and PowerWorld is utilized to run power flow analysis and display the fault location results [7].

3) Cascading Event Analysis

Power system cascading event is quite often a very complex phenomenon with low probability of occurrence but potentially with catastrophic social and economic impacts. Recent study reveals that early and proper control actions at the steady state stage can prevent a possible cascading event from unfolding. Power system operators lack sufficient analysis and decision support tools to take quick corrective actions needed to mitigate unfolding events. Cascading event analysis aims at detecting cascading event at an early stage, and preventing it from unfolding [8].

4) Reliability-Centered Maintenance of Circuit Breakers and Transformers

Reliability-centered maintenance (RCM) is a cost-effective maintenance scheduling mechanism. It prioritizes maintenance activities based on quantification of likelihood and consequence of equipment failures. The two most common types of equipment, transformers and circuit breakers are selected because: 1) expenditures for maintenance of this equipment represent a large percentage of maintenance budgets; 2) failures adversely affect system reliability; and 3) monitoring technologies presently exist within substations. Three steps are included in RCM of transformers and circuit breakers: Failure mode identification, failure rate estimation and maintenance-scheduling based on risk reduction [9].

B. Formulation of Use Cases

Five use cases have been created to study the requirements from the applications addressed above: alarm processing, fault location, cascading analysis, reliability-centered maintenance and substation-level data acquisition. Use case of substation-level data acquisition focuses on substation responding to request from control center or other substations, collecting data from different IEDs and sending it to different destination. Fig. 2 is a diagram of the communication paths. Table I provides all actors participating in five use cases.

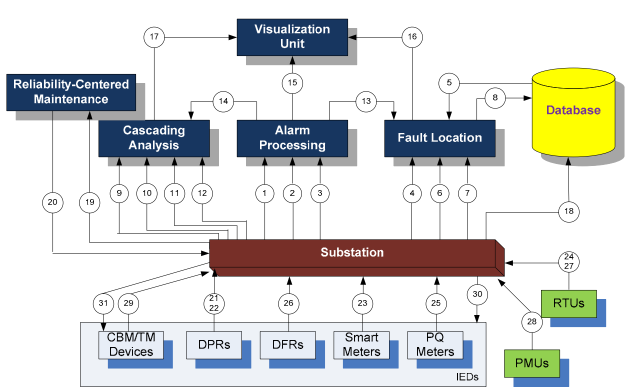

Fig. 2. Communication paths.

TABLE I
LIST OF ACTORS

Actor	Domains	Description
IEDs	Transmission	A microprocessor-based device aimed at controlling and monitoring power system equipment and communicating with SCADA, as well as distributed intelligence applications
Substation Application	Transmission	Substation is a point in transmission and distribution system where voltage is transformed from high to low or the reverse using transformers.
SCADA	Operations	A computer system that monitors and controls power system operations. SCADA database is updated via remote monitoring and operator inputs.
WAMS	Operations	System consisting of phasor measurement units located in a wide area of power systems and determining actions to perform with transmission actuators.
Metering System	Customer	The systems used for collecting revenue and operator metering information.
GIS	Operations	An information system that integrates, stores, edits, analyzes, shares, and displays geographic information.
Control Center	Operations	Center for power system centralized operations.
EMS	Operations	A system of computer-aided tools used by operators in electric utility grids to monitor, control, and optimize the performance of the generation and/or transmission system.

Explanation of each communication path in Fig. 2 is provided in Table II. Data to be communicated is categorized into four classes: 1) raw data, 2) pre-processed data from substation 3) reports and 4) historical data. Raw data is the data collected by SCADA without pre-processing at substation level, and data collected by substation IEDs before sending to centralized system. It is not directly used in application other than for archiving. Substation information massage contains information about CB Status, PF data, DFR event reports, alarms, relay operation reports, synchronized samples, real-time load and connectivity information and other information that has been received by substation application from RTUs and other IEDs, and selected and processed at the substation level. Reports refer to the analysis reports generated by different applications and exchanged among various departments in the control center. Historical data is the data retrieved from the database and serves in some of the algorithms for optimized fault location.

TABLE II
EXPLANATION OF COMMUNICATION PATHS

NO.	Data	From	To	Class	Requirements
1	CB Status	Substation	Alarm Processing	2	Real-Time
2	Over Current Alarm	Substation	Alarm Processing	2	Real-Time
3	Relay Operation Report	Substation	Alarm Processing	2	Real-Time
4	Power Flow Data	Substation	Fault Location	2	Real-Time
5	Historian	Database	Fault Location	4	Offline
6	Event files	Substation	Fault Location	2	Real-Time
7	System Info.	Substation	Fault Location	2	Real-Time
8	Request	Fault Location	Database	--	--
9	Synchronized Samples	Substation	Cascading Analysis	2	Synchronization
10	Power Flow Data	Substation	Cascading Analysis	2	Real-Time
11	System Information	Substation	Cascading Analysis	2	Real-Time
12	Event files	Substation	Cascading Analysis	2	Real-Time
13	Alarm report	Alarm Processing	Fault Location	3	--
14	Alarm Report	Alarm Processing	Cascading Analysis	3	--
15	Alarm Report	Alarm Processing	Visualization Unit	3	--
16	Fault Location Report	Fault Location	Visualization Unit	3	--
17	Cascading Report	Cascading	Visualization Unit	3	--
18	Raw Data	Substation	Database	1	--
19	Condition info.	Substation	Maintenance	2	Real-Time
20	Request	Maintenance	Substation	--	--
21	Over Current Alarm	DPRs	Substation	2	Real-Time
22	Relay Operation Report	DPRs	Substation	3	Real-Time
23	Power Flow Data	Smart Meters	Substation	1	Real-Time
24	Power Flow Data	RTUs	Substation	1	Real-Time
25	Power Flow Data	PQ meters	Substation	1	Real-Time
26	Event files	DFRs	Substation	1	Real-Time
27	System Info.	RTUs	Substation	1	Real-Time
28	Synchronized Samples	PMUs	Substation	1	Synchronization
29	Condition info.	CBM/TM devices	Substation	1	Real-Time
30	Request	Substation	IEDs	--	--
31	Request	Substation	CBM/TM devices	--	--

C. Application Requirements

Among the four applications, cascading event analysis is the one that has the most critical requirement on communication latency. As cascading events develop very fast (often in minutes, sometimes in seconds) and the consequence is extremely severe, the speed for cascading analysis must beat the speed of system deterioration. This means that the total time from data being collected from different sensors to system operators receiving report from cascading analysis software must be less than a few minutes, otherwise cascading analysis would become meaningless.

Cascading analysis is activated by detection of cascading events, which is done by alarm processing, and results from alarm processing serve as part of the input for cascading event analysis, making alarm processing also time-critical.

Fault location has a more relaxed requirement on time, while communication for reliability-centered maintenance is the least time-critical. When it comes to communication, the requirements from alarm processing and cascading analysis are as follows:

- Integrated data packaging in substation;
- Efficient data extracting in control center;
- Latency for data transmission;
- Congestion management.

IV. STANDARDS RELATED TO TRANSMISSION-LEVEL COMMUNICATION

Our research has addressed standards and guidance associated with transmission-level communication in three groups: data exchange, communication protocol and interface, and cyber security.

A. Data Exchange

IEC 61970 [10]: this family of standards provides a Common Information Model (CIM) necessary for exchange of data between devices and networks, primarily in the transmission domain. Information exchanged among control center systems using CIM for application-level energy management system interfaces is also defined.

IEC 61850 [11]: this standard facilitates substation automation and communication as well as interoperability through a common data format. This standard defines communications within transmission and distribution substations for automation and protection applications. It is being extended to cover communications beyond the substation to include integration of distributed resources and communications between substations.

IEC 60870-6 [12]: this standard facilitates exchange of information between control centers.

IEEE C37.118 [13]: this standard defines phasor measurement unit (PMU) performance specifications and communications.

IEEE 1588 [14]: this is the standard for time management and clock synchronization across the Smart Grid for equipment needing consistent time signal management.

IEEE 1686-2007 [15]: this is a standard that defines the functions and features to be provided in substation intelligent electronic devices (IEDs) to accommodate critical infrastructure protection programs. The standard covers IED security capabilities including the access, operation, configuration, firmware revision, and data retrieval.

B. Communication Protocol and Interface

ANSI C12.18/IEEE P1701/MC1218 [16]: Protocol and optical interface for measurement devices.

IETF RFC 2460 (IPv6), IETF RFC 791 (IPv4) and more [17]: these suites of standards define foundation protocol for delivery of packets in the Internet network.IPv6 is new version of the Internet Protocol that provides enhancements to IPv4 and allows a larger address space.

C. Cyber Security

IEC 62351Part 1-8 [18]: this family of standards defines information security for power system control operations.

DHS Cyber Security Procurement Language for Control Systems [19]: The National Cyber Security Division of the Department of Homeland Security (DHS) developed this document to provide guidance to procuring cyber security technologies for control systems products and services - it is not intended as policy or standard. Because it speaks to control systems, its methodology can be used with such aspects of smart grid systems.

V. Communication Solutions for Specific Applications

A. Communication Infrastructure

Fig. 3 shows a generic communication architecture that connects all substations in an information network [20]. The communication infrastructure is shown as a three-level hierarchy. Each substation has its own high speed local area network (LAN) which ties all the measurements and local applications together. Each substation also has a server that connects to the higher level communication network through a router. LAN within control center receives data and sends it to different applications (after pre-processing, if necessary). Thus all applications that require data from more than one substation, i.e., applications that are not local, have to use this higher level network for gathering input and sending output.

Networks for the three levels are to be designed with thorough consideration.

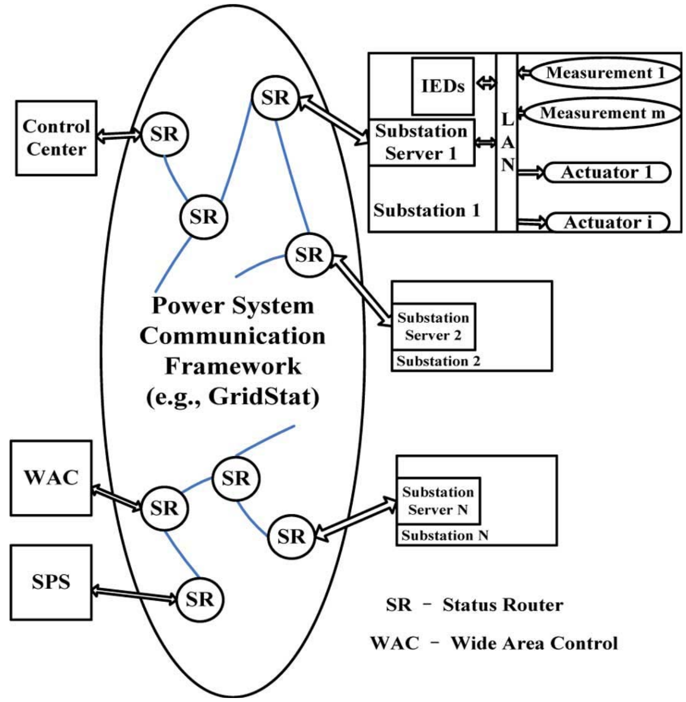

Fig. 3. Real-time information infrastructure for the electric power grid [20].

B. Selection of Communication Solutions

The architecture shown in Fig. 3 assumes a significant infusion of new measurements and communications and control devices. It is not going to happen overnight, but will have to be phased in over many years both because of the costs involved as well as the fact that the system has to be fully operation.

To build an efficient communication system for system operation and control, communication solutions for the new transmission-level applications must take following issues into consideration:

- *Integration of energy management solutions.* This solution needs to combine different systems such as security, video, on-site generation, appliance control, environmental control, and energy efficiency using a complex communication network.
- *Optimization of IED data exchange infrastructure that covers RTUs, PMUs, relays, and recorders.* The concept of data integration and information exchange will require that filed data be brought to common databases, processed, and then the resulting information will be disseminated to a variety of users [21].

In selection of communication solutions requirements, focus on different aspects of communication solutions is needed: technical characteristics, cost, life cycle assessment, deployment strategy, standardization, and utility performance impact. The following are examples of expected outcomes:

- *Technical Characteristics.* This will include study of different communications requirements as defined by the International Standards Organization's Open System Interconnection standard seven layer communication architecture.

- *Cost.* The study will define a methodology for evaluating the cost of installing new communications infrastructure and integrating it with existing infrastructure, spanning from capital investments to the maintenance and OEM cost for upgrades and refurbishment.
- *Life cycle assessment.* This often neglected or misunderstood subject will be explored in the context of totally new communication facilities such as fiber or wireless that may have to be used to replace or supplement existing facilities.
- *Deployment strategy.* While this issue may heavily depend on the individual utility's needs, generic requirements to be studied are: allocation of applications to communication solutions, integration of new and existing infrastructure, cyber security enforcement, and standards compliance.
- *Standardization.* This area requires full understanding of the new features of advanced communications such as data formats, data models, communication protocols, configuration data and communication media. All the aspects need to be associated with selected applications.
- *Performance impacts.* Besides the traditional communication infrastructure impacts such as reliability and security, more peculiar communication impacts such as sample time reference synchronization, real-time information latency, and component and system aging need to be explored.

C. Case study of Communication Solutions: Substation Network Design

The tradition serial communication options still play a dominant role in the utility legacy systems, which consist of equipments at one or more control centers, at substations, and along feeders. This serial communication architecture has evolved over time to facilitate the interconnection of many different types of equipment using various serial protocols. The serial channels can be point-to-point and point- to-multipoint.

The remote terminal unit (RTU)/data concentrator function typically supports many signal input channels at a time and provides local I/O interfacing and communication protocol conversion. Separate dedicated or ad-hoc communication channels are required for maintenance and non-operational data retrieval. The advantages of using this serial communication mechanism are [22]:

- Serial communication architectures are more reliable and less expensive compared with Ethernet based networks;
- For small systems with small measurement point counts, low speed serial systems can still meet their intended functional requirements;
- Security requirements for serial communications may be cheaper and easier to meet, which is very sensitive issue in the future Smart Grid communication network platform.

From the perspective of long term development for substation automation system and huge volumes of data brought with the Smart Grid, the networked communication architectures provide more advantages.

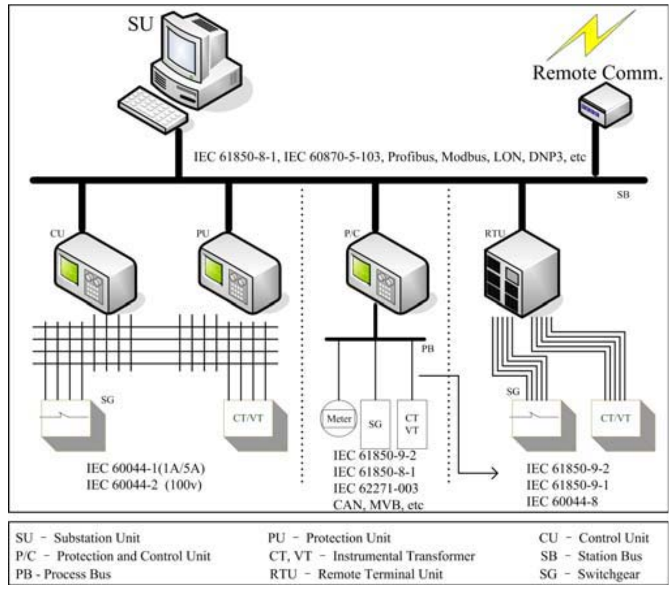

Fig. 4. Sample hybrid-tech substation communication network.

Fig. 4 shows an example of a hybrid-tech communication system using a communication network infrastructure, which is featured by several benefits as listed below:

- An Ethernet LAN in a substation along with a high speed digital communication interconnection to the control center greatly increases the available communication bandwidth;
- Engineers can upload additional information from IEDs with minimal impact (assuming adequate bandwidth) to other processes (e.g., SCADA) and without additional hardware. Each IED merely has to provide another protocol port number for file or auxiliary data transfer;
- The added bandwidth and multi-protocol capabilities of modern network protocols mean that a separate maintenance port may only be needed to setup the initial parameters to get the device on the network.

VI. Conclusion

This paper discusses concerns in communication system for transmission system operation, protection and maintenance. The following problems are addressed and answered:

- New requirements from emerging applications. The retrofitted or redesigned communication systems under the development of smart grid may fit implementation of these applications by meeting such requirements.
- Related standards. As a contribution to the standardization study, existing standards are surveyed, classified, and highlighted according to its importance to our study.
- Concerns in selection of communication solutions. Recommendations for a staged deployment/integration path are outlined.

VII. Acknowledgement

The authors would like to take this opportunity to thank Mr

Feng Xu and Ms. Biljana Matic-Cuka for their contribution in the study of substation communication.

VIII. References

[1] "Energy Independence and Security Act of 2007" H.R. 6--110th Congress, 2007.

[2] Office of the National Coordinator for Smart Grid Interoperability, "NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0," *NIST Special Publication 1108*, January 2010. Available: http://www.nist.gov/public_affairs/releases/upload/smartgrid_interoperability_final.pdf

[3] [online] Available: http://www.smartgrid.epri.com/Repository/Reposito y.aspx

[4] Subgroup of NASPI Data and Network Management Task Team (D&NMTT), "Statement of Work: Specification for North American SynchroPhasor Initiative (NASPI)," *Interim Rreport for National Energy Technology Laboratory (NETL)*, May 2008. Available: http://www.naspi.org/resources/dnmtt/naspinet/quanta_sow.pdf

[5] M. Kezunovic, Yufan Guan, "Intelligent Alarm Processor," *ERCOT Final Report*, March 2008.

[6] M. Kezunovic, B. Perunicic, "Automated transmission line fault analysis using synchronized sampling at two ends," *IEEE Trans. Power Systems*, Vol. 11, pp. 441-447, February 1996.

[7] M. Kezunovic, "Optimized Fault Location," *PSerc Project T-32 Final Report (08-07),* April2008.

[8] M. V. Venkatasubramanian, M. Kezunovic and V. Vittal, "Detection, Prevention and Mitigation of Cascading Events," *PSerc Project S-29 Final Report (05-59) - Part I*, September 2008.

[9] M. Kezunovic, "Automated Integration of Condition Monitoring with an Optimized Maintenance Scheduler for Circuit Breakers and Power Transformers," *PSerc Project T-19 Final Report,* Nov. 2007.

[10] Common Information Model (CIM), *IEC Standard 61970,* Dec. 2005.

[11] Communication Networks and Systems in Substation, *IEC Standard 61850,* Aug. 2010.

[12] Telecontrol equipment and systems - Part 6: Telecontrol protocols compatible with ISO standards and ITU-T recommendations, *IEC Standard IEC/TR 60870-6*, May 1995.

[13] IEEE Standard for Synchrophasors for Power Systems, *IEEE Std. C37.118–2005 (Revision of IEEE Std. 1344–1995),* March 2006.

[14] IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems, *IEE Standard 1588-2008,* July 2008.

[15] IEEE Standard for Substation Intelligent Electronic Devices (IEDs) Cyber Security Capabilities, IEEE Standard 1686-2007, Jan. 2008.

[16] Protocol Specification for ANSI, *American National Standard ANSI C12.18-2006,* May 2006.

[17] Internet Protocol, *IETF Std. RFC 2460(IPv6),* Dec, 1998.

[18] Power systems management and associated information exchange - Data and communications security, *IEC/TS Std. 62351,* May 2007.

[19] "Cyber Security Procurement Language for Control Systems," *Report from the Department of Homeland Security*, Sept. 2009. Available: http://www.us-cert.gov/control_systems/pdf/SCADA_Procurement_DHS_Final_to_Issue_08-19-08.pdf

[20] A. Bose, "Smart transmission grid applications and their supporting infrastructure," *IEEE Trans. Smart Grid,* vol. 1, pp. 11-19, June 2010.

[21] M. Kezunovic, A. Abur, A. Edris, D. Sobajic, "Data Integration/Exchange Part II: Future Technical and Business Opportunities," *IEEE Power & Energy Magazine,* pp 24-29, May/June 2004.

[22] Recommended Practice for Network Communication in Electric Power Substations. IEEE Standard 1615, 2007.

IX. Biographies

Yimai Dong (S'07) received her B.S. and M.S. degrees from North China Electric Power University, Beijing, China, in 20*05, 2007 respectively, all in* electric engineering. She has been with Texas A&M University pursuing her Ph.D. degree since August 2007.

Her research interests include applications in power system protection, distribution outage management and communication for power system operation.

Mladen Kezunovic (S'77-M'80–SM'85–F'99) received the Dipl. Ing., M.S. and Ph.D. degrees in electrical engineering in 1974, 1977 and 1980, respectively. Currently, he is the Eugene E. Webb Professor and Site Director of Power Engineering Research Center (PSerc), an NSF I/UCRC.at Texas A&M University He worked for Westinghouse Electric Corp., Pittsburgh, PA, 1979-1980 and the Energoinvest Company, in Europe 1980-1986, and spent a sabbatical at EdF in Clamart 1999-2000. He was also a Visiting Professor at Washington State University, Pullman, 1986-1987 and The University of Hong Kong, fall of 2007. 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 a Fellow of the IEEE, member of CIGRE and Registered Professional Engineer in Texas.