Energy Router: Architectures and Functionalities toward Energy Internet

Yi Xu, Jianhua Zhang, Wenye Wang, Avik Juneja, and Subhashish Bhattacharya
Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Center
Department of Electrical and Computer Engineering
North Carolina State University
Raleigh, NC, USA
Email: {yxu2, jzhang25, wwang, ajuneja, sbhatta4}@ncsu.edu

***Abstract*—The next-generation electric power system, known as the smart grid, will incorporate a large number of renewable energy resources that fundamentally change the energy management paradigm. In order to manage efficiently the energy supply and demand in the power grid, energy routers are required which adjust dynamically the energy distribution in the grid, which is so called the Energy Internet. We discuss in this paper the functional expectations on the energy router design and present our preliminary research results on the energy router architectural construction and communication performance. This paper documents our work-in-progress on the design and implementation of energy router, a critical equipment to enable intelligent energy management in the smart grid.**

I. Introduction

In recent years, the increasing concern with the global energy shortages and environment problems has spurred worldwide active research on the next-generation electric power system, which is known as the *smart grid* that features renewable energy resources and intelligent energy management. A remarkable change of energy exploitation is anticipated in the smart grid, which shifts from heavy dependence on fossil fuels to distributed and diversified renewable energy resources, such as sunlight, wind, hydro, tide, geothermal, and waste [1]. Besides the utilization of renewable energy resources, the smart grid is meanwhile an overall upgrade of the legacy electric power systems in energy management [2]. In traditional power systems, energy flows unidirectionally from the power plants to the customers, characterized by centralized power generation and one-way energy transmission. In comparison, the smart grid supports a distributed and flexible energy management paradigm. In this revolutionary energy management system, energy is generated by maximally utilizing the renewable resources in a distributive fashion and a significant portion of the gird users are both energy producers and energy consumers [3], [4].

The dual roles of grid users resemble those of the Internet users: every Internet user is both a contributor and a beneficiary of the information exchanged on the web, and every grid user may both sell and buy energy from the grid. The similarity between the energy flows and the information flows has entitled the name *Energy Internet* to the smart grid [5]. In the Internet, packet routers play a vital role in transporting information. Similarly, in the smart grid, we need *energy routers* to manage the transmission and distribution of electricity. Energy routers will serve as a critical component in the smart grid.

As the smart grid is an emerging research field that still stays in the primitive research phase, there is no reported research result on the design of energy routers. In this paper, we attempt to provide a high-level overview of the functional expectations and research challenges on the energy router design. Indicated by the name, the energy router is a technological combination of power transmissions and information exchanges. It undertakes two major tasks, namely, *dynamic adjustments of energy flows* and *real-time communications between power devices*, which also interact with each other. As such, we will discuss the respective functional requirements on the energy router for energy controls and inter-device communications, as well as their integration into an intelligent energy management entity. Besides the functional requirements, we also present our framework design of the energy router and our preliminary experimental results on the communication support for energy router. The work in this paper presents our current vision and available results, and hence we also discuss our next-step research directions.

The rest of this paper is organized as follows. In Section II, we outline the main features of the smart grid and map them into the functional expectations on the energy router. In Section III, we discuss in details the requirements on energy router design from three perspectives, namely, power electronics, communications, and control intelligence. We present our energy router framework design in Section IV, and its communication support in Section V. Our prospective research work is discussed in Section VI. We finally conclude this paper in Section VII.

II. Smart Grid and Energy Router: Functional Expectations

In order to understand the critical dependence of the smart grid on energy routers, we first outline the functions expected for the smart grid and then discuss how the energy routers support these functions. As a comprehensive upgrade of the existing power systems, the smart grid embraces a large number of new features, among which the most important ones

978-1-4577-1702-4/11/$26.00

are the inclusion of renewable energy resources and the intelligent energy management that optimizes the energy usages. Specifically, the functions of smart grid can be categorized into the following seven domains [6], [7]: bulk generation, transmission, distribution, operation, market, customer, and service provider. The energy router is an enabling technological component in the smart grid operations. We discuss next the usages of energy routers in each domain.

A. Energy Router Usages in Smart Grid

1) Bulk Generation Domain: Energy is generated largely from distributed energy resources. These energy sources are usually connected to their local electrical loads. When the local supply exceeds the local demand, the surplus energy flows into the grid through energy routers. At time of local energy deficit, the grid provides the insufficient amount of energy through the energy router.

2) Transmission Domain: The transmission domain is responsible for energy transmission from the generation sources to the consumers. Given the distributed energy resources, the transmission domain needs to dynamically dispatch energy from the energy sources that have surplus amount after satisfying their local demands. Energy routers are hence needed to implement the dynamic energy flows.

3) Distribution Domain: The energy distribution is implemented through energy routers. When the user demands vary over time, the energy routers also take the responsibility of tracking the demand changes to adapt the energy distribution dynamically.

4) Operation Domain: In order for the operations to be optimized, grid status information must be collected, such as the current energy generation capacities in distributed energy resources and the current energy demands from different customers. This status information is obtained from the energy routers used in the transmission and distribution domains.

5) Market Domain: As this domain aims to achieve a balance between the supply and the demand, the energy supply and demand information must be gathered from various parts of the grid in order for the market domain to operate correctly. The information collection depends on the energy routers deployed across the grid.

6) Customer Domain: Customers purchase energy from the grid through energy routers. When the customers also generate energy from renewable resources, the energy routers regulate the energy demand and supply for their connected customers. If the aggregate amount of energy produced by the customers exceeds their own demand, the superfluous amount is sold back to the grid through energy routers.

7) Service Provider Domain: The providers either have their own energy generation facilities or purchase energy from the distributed renewable energy resources, and sell the energy to customers. They need to have the current energy supply and demand information to optimize their service. The information acquisition relies on the energy routers.

B. Energy Router Functions: User and Grid Levels

Our discussion shows that the energy routers are the fundamental equipments required in the construction of smart grid. As they are used pervasively in the grid, they undertake a wide range of functions. Similar to the Internet routers, the energy routers have different location-dependent tasks, which can be generally categorized as the user-level functions and the grid-level functions.

1) User Level Functions: When an energy router is located at the edge of grid, it is connected directly to the customers. There are a total of three main types of users: distributed renewable energy resources, distributed energy storage devices, and the loads. These users construct a microgrid that hosts the energy router as its central coordinator. Each user in the same microgrid talks with the energy router for all the energy services. We discuss below all the user level functions required at an energy router.

- User Attachment. The smart grid features an easy-to-use plug-and-play energy interface. When a user connects to the smart grid through the energy router, the energy router is responsible for discovering new user attachments and configuring them for correct operations.
- Service Request. When the attached user wants to start some kind of services, the user sends "service request" message to the energy router. The energy router then replies "service acceptance" message back to the user and controls the solid state transformer to provide the energy service.
- Status Update. The user sends the "status update" message to the energy router when the user status changes. The energy router updates its current user status.
- Service Termination. When the user terminates the service, it sends the "service termination" message to the energy router and then disconnects from the energy router. The energy router informs the solid state transformer to stop power output to this user.
- User Detachment. When the user disconnects from the grid, the energy router detects the disconnection and updates its user interface accordingly. The detection is made possible by periodically probing the user existence and listening to the user acknowledgments. If the energy router does not hear back from a user for a defined period of time, the user is believed to be disconnected.

2) Grid Level Functions: An energy router is not only connected to the energy customers, it also communicates with the other energy routers in the grid to implement smart energy management. There are two connection modes for an energy router to manage its microgrid. They are namely the *grid tie mode* and the *islanding mode*.

In the grid tie mode, the energy router connects its microgrid to the smart grid and energy flows into and out of the microgrid through the energy router. The energy router functions as an energy flow regulator in response to the energy supply and demand in the microgrid. In the islanding mode, the energy router disconnects the microgrid from the grid for protection.

The local loads must be accommodated by the distributed renewable energy resources and the distributed energy storage devices in the microgrid. In order to maximize the operational duration, the energy router minimizes the electricity usages of low priority tasks. A few typical operational scenarios are discussed below.

- During the sunny daytime, when the photovoltaic system is ready to convert solar energy into electricity, it sends the energy generation request to the energy router. The energy router checks the local power demand, which includes the current load demand and the energy capacity of the distributed energy storage devices, and then confirms with the photovoltaic system to start solar energy conversion.
- At the sunset, the photovoltaic system stops energy generation and the load demand increases. The photovoltaic system sends the service termination message to the energy router and disconnects from the grid. The energy router informs the distributed energy storage devices to start energy supply.
- During the early night, the wind turbine may be ready to generate electricity. It sends the service request to the energy router. The energy router confirms with the wind turbine to start electricity conversion and injection into the microgrid. If the amount of electricity generated by the wind turbine is more than the local demand, the surplus is sold back to the grid. Otherwise, the energy router requests the insufficient amount from the grid.
- In the late night, the load becomes lighter. The energy router begins to charge the plug-in electric vehicles for use in the next morning and charge the distributed energy storage devices for use in the next time of temporary electricity shortage.
- During the daytime, when the price of electricity is the lowest for residential users, the energy router of residential users schedules most of the energy usages in its microgrid. On the contrary, for industrial users the price of electricity is the highest during the daytime, and their energy routers may schedule the non-urgent tasks to the night time. The energy routers hence determine the electricity usages dynamically according to the costs.

III. Energy Router Design Requirements

The energy router undertakes important electricity control functions to enforce correct and efficient energy management in the smart grid. It is a technological integration of power electronics, communications and automations. Therefore, its design requirements include the following three aspects.

A. Power Electronics Requirements

Power electronics are required in the energy router to implement automatic energy distributions and management. As observed from the application scenarios discussed above, an energy router collects the electricity demand and supply information in real-time from the grid and dynamically adjusts the electricity allocation in accordance with the demand and supply information. Power electronics serve as the interface between the intelligent management module and the solid state transformer in an energy router. The power electronics must be able to operate fast and reliable to ensure the correct enforcement of the commands issued by the intelligent management module.

B. Communications Requirements

The operations of energy router depend on the grid status information it collects. For example, the energy router turns on the photovoltaic system to generate electricity when it detects that the local load increases, and switches off a power device when it detects that the device is not working properly. The communications between energy routers must satisfy three requirements.

1) Transmission Latency: The communication latency defines the maximum time in which a particular message should reach its destination through a communication network. The messages communicated between energy routers may have different network latency requirements [8], [9], depending on the type of events that trigger the messages. The most time critical messages in the smart grid require a delivery latency as small as 3 milliseconds. Hence, the energy routers must have sufficiently fast processing and communication capabilities to guarantee low latency information exchanges.

2) Communication Reliability: The communications between energy routers must be reliable [10]–[12]. The energy routers must be designed with the failure probability minimized. In addition, the energy routers must have communication failure detection capability to retransmit the lost messages quickly. In case that the energy routers encounter equipment failures, the remaining energy routers should be able to continue communications through bypassing paths.

3) Information Security: The information exchanged between energy routers contains grid operation instructions. Falsified or impersonated messages will jeopardize the grid operations. Therefore, the energy routers must ensure the communications to be secured. Properly designed security mechanisms are required to prevent unauthorized users from reading and changing the information communicated between energy routers. In case that malicious users inject falsified messages, the energy routers should be able to detect the falsification and discard these messages.

C. Distributed Grid Intelligence

In addition to the power electronics and communications, the energy routers must have the distributed grid intelligence module to make informed judgments regarding the energy management in the grid. This grid intelligence module utilizes the information collected through the communication module and determines the control changes to be made in the grid through the energy router cooperations. As each energy router takes charge of a microgrid, the intelligent grid operation decisions are reached by combining and processing the distributed grid status information collected from different energy routers.

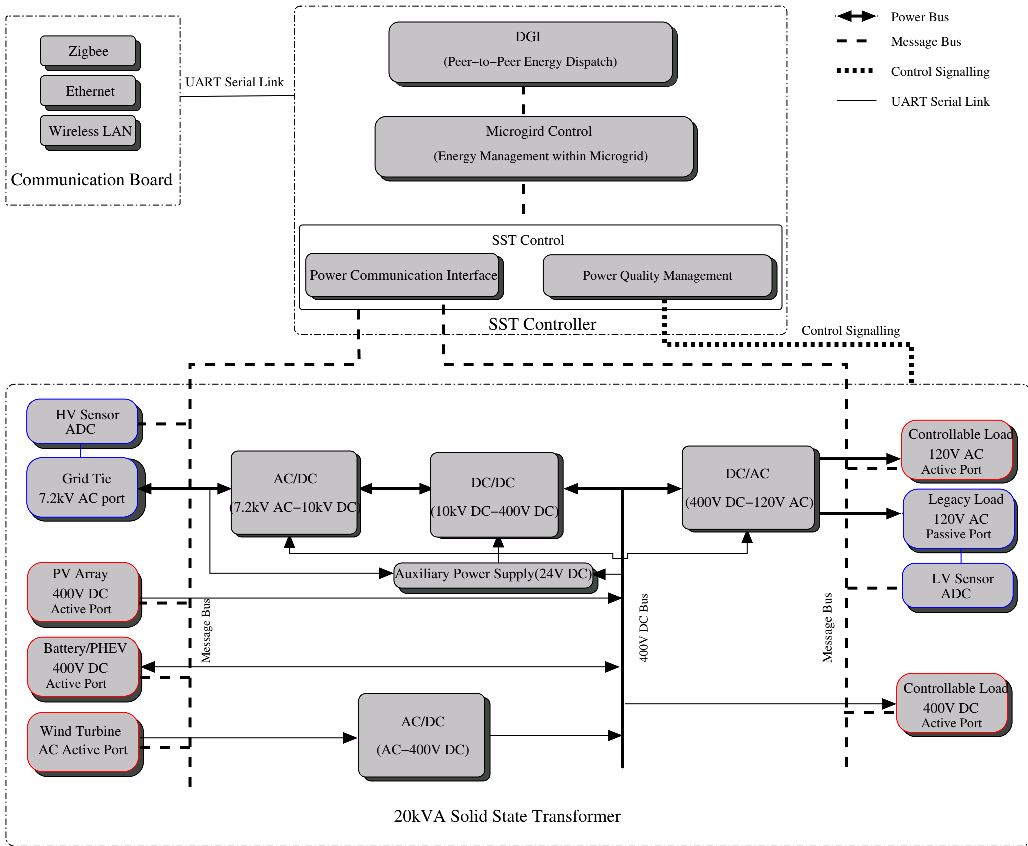

Fig. 1. The architectural design of an energy router based on a 20 kVA solid state transformer.

IV. Energy Router Architectural Design

In this section, we propose an energy router architecture that incorporates the power electronics, communications and the distributed grid intelligence modules. In power transmission and distribution systems, the voltages and currents vary in a large range, depending on the equipment locations. We use a 20 kVA solid state transformer as an example in our proposed energy router design. The energy router architecture proposed in this paper can be applied to other solid state transformers with different load capacities after slight modifications. We illustrate our energy router architecture in Fig. 1.

A. Power Electronics Module

The core functions of the power electronics module is to convert the electricity from high voltages on the transmission lines to different levels of low voltages suitable for use by the electrical appliances. As such, this module consists of a series of sub-transformers connected in sequence to convert voltages, for example, from 7.2 kV AC to 10 kV DC, from 10 kV DC to 400 V DC, and from 400 V DC to 120 V AC. The power supply to the sub-transformers can be obtained from the output of sub-transformers. As the interfaces to different electrical appliances, the sub-transformers are connected to various electrical ports. These ports provide plug-and-play electricity services to many electrical appliances as well as the connection to the smart grid.

B. Communications Module

The communications module in the energy router consists of two components, one for the intra-communications inside the energy router and the other for the inter-communications between different energy routers. The intra-communications component is also called the power communications interface in the architecture shown in Fig. 1. This component manages the communications between the controller of the solid state transformer and each electrical port. The inter-communications component can be designed as a dedicated communication board built with an embedded system. It provides communication facilities to connect to the information exchange infrastructure in the smart grid. The network access technologies include ZigBee, Ethernet and wireless LAN. The communication board can be either a stand-alone board separate from the SST controller board or an integrated part of the SST controller board. If it is a separate board, the connection between the two boards can use serial link, USB or other possible technologies. In Fig. 1, serial link is used as an example.

C. Grid Intelligence Module

The grid intelligence module is integrated into the SST controller board. It collects the energy router status information from the communications module and manages the optimized energy generation and distribution both inside the microgrid

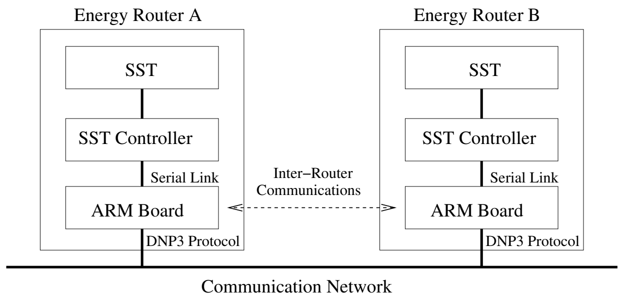

Fig. 2. The communications module in energy router implemented as an ARM board.

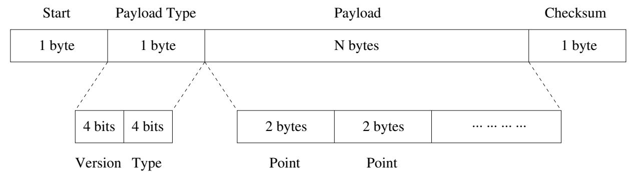

Fig. 3. The packet format for ARM-SST communications protocol.

and between peer-to-peer microgrids. The operational decisions of the intelligence module are communicated to the power quality management component, which is responsible for changing the solid state transformer configurations accordingly. Typical changes include for example port activations, appliance attachments, and grid connections.

V. Communications Module Implementations and Experiments

We have implemented a prototype communications module for our proposed energy router architecture. This module is built as a stand-alone embeded system and connected to the controller of the solid state transformer (named as SST controller in this paper) through a universal asynchronous receiver/transmitter (UART) serial link. The communications modules of different energy routers exchange information through a communication network. A sketch of the communications module and its connections to other energy router components is illustrated in Fig. 2.

A. Implementations

We have used the Technologic Systems TS7250 embedded system (named as ARM board in this paper) to build the communications module. The ARM board is a general purpose single board computer with 200 MHz ARM CPU and 64 MB RAM, which runs a modified Linux kernel and provides different communication interfaces such as WiFi, Ethernet, USB, and serial ports. The SST controller is implemented as a separate board to sample status values from and change configurations to the solid state transformer. In order to allow communications between the ARM board and the SST controller board, an ARM-SST serial communication protocol has been set up (explained next) to work over the UART interfaces on the two boards.

The ARM board functions as the external communication interface to peer energy routers. Many network technologies can be used to connect the ARM boards in different energy routers, such as the Ethernet, wireless LAN, and ZigBee. We have implemented all the three types of connections. However, the network connections alone are not sufficient to support the information exchange functions. A network and transport layer protocol must be used to ensure reliable communications. The Distributed Network Protocol (DNP3) has been used in our prototype.

1) ARM-SST Communications Protocol: We have designed a protocol for the ARM-SST communications by defining the packet format exchanged between the ARM board and the SST controller board. As shown in Fig. 3, the packet format contains several fields. The "start" field signifies the beginning of the packet, the "payload type" field represents whether the packet contains set points or all points. The "payload" from ARM to SST controller consists of 6 set points of 2 bytes each, whereas the "payload" from SST controller to ARM consists of the received 6 set points along with 12 analog points. The last byte accounts for the packet checksum.

When an ARM board receives the control commands from the network, the commands are forwarded to the SST controller using the UART serial link. The set points received by SST controller are responsible for controlling the interfacing power devices, such as relays and circuit breakers. In response to the set points, the SST controller acknowledges the ARM by sending the same control points appended with the current status field of the stored structure (analog points). The stored structure is periodically updated based on the input values from the I/O ports. Upon receiving a new set point from the network, the ARM board continuously sends out set points to the SST controller until it receives an acknowledgment.

2) Distributed Network Protocol: The DNP3 is an open, robust and efficient network protocol designed specifically to operate reliably in harsh environment of the electric utility automation systems. It can be used to monitor a number of physical processes and information states, such as electricity consumption, voltage, current, and temperature at a remote location over a communication network. The DNP3 protocol supports communications over TCP/IP stack. We use DNP3 as the network protocol between the communication modules of different energy routers.

B. Experiments

We have experimented with our prototyped communications module to measure the packet delay, which is an important performance metric in power system communications as the time critical commands in power systems must be promptly transmitted and delivered. Particularly, we have tested the packet delays in three scenarios. In each scenario, packets of variable length (from 16 to 4096 bytes) are transmitted through the DNP3 protocol, which in turn runs over TCP/IP protocol stack.

- TS7250-TS7250 via Ethernet. Two TS7250 embedded systems are connected through a 100 Mbps Ethernet

switch. Each TS7250 is equipped with a 200 MHz ARM-9 CPU and 64 MB memory, and installed with Linux operating system. The measured packet delays vary between 0.8 and 1.6 milliseconds.
- TS7250-TS7250 via 802.11b. Two TS7250 embedded systems are attached with WiFi dongles on their USB ports and communicate by connecting to a shared 802.11b access point. The measured delays vary between 3.2 and 17 milliseconds.
- TS7250-ZigBee gateway. A TS7250 embedded system is attached with an Xbee-Pro communication board through serial link and exchanges data with an 802.15.4 ZigBee gateway. The measured delays vary between 12 and 86 milliseconds.

The most time critical messages in smart grid communications require a delay bound as small as 3 milliseconds. It is however observed from the experimental results that the actually achieved communication delays exceed the bound in all the wireless networks that have been tested. Note that the delay performances will become even worse when the networks experience heavier background traffic loads or more complicated multihop networks are used. Thus, it remains a challenging research problem to speed up the packet transmissions between the communications modules in different energy routers.

VI. Prospective Work

The work presented in this paper is our vision on the construction of energy router and our preliminary results on its communication perspective. There is still much more work to do to implement the energy router. Our next-step work can be categorized into the following three directions, in accordance to our three identified functional modules.

- We are currently trying to build the SST controller board and connect it to the solid state transformer. The SST controller board will consist of a DSP chip and a FPGA chip, which are programed to automatically read the SST status information and change the SST configurations when necessary.
- The communications module needs improvement on the communication delay. Our current experimental results show that the packet delay with wireless networks is significantly larger than that with the Ethernet. However, wireless networks will be an important communication facility in power systems. Therefore, further work is required to investigate the methods to shorten the packet delay in wireless networks. Communication reliability and security will also be studied.
- The grid intelligence has not been studied in our current work. It plays an important role in the grid to achieve efficient energy management. Building this module requires insightful understanding of the energy distribution in the grid and advanced software for automated real-time decision making to dynamically adjust the energy router operations.

VII. Conclusion

In the future smart grid, energy router will be a fundamental and indispensible equipment to support the smart energy management. We have discussed in this paper the functional expectations on the energy router design in relation to the energy router usages in the grid under various operational scenarios. Based on the functional analysis, we have proposed an architecture for the energy router design, which composes three modules in charge of the power electronics, communications and grid intelligence, respectively. We have also implemented partial functions of the communications module and measured the delay performance of this module. Our experimental results suggest that further research is needed in order for the energy routers to have satisfactory communication performance over wireless networks. Finally, we have discussed our next-step work on the energy router design and implementation. This paper summarizes our progress toward energy router construction and we hope the work presented in this paper advances our understanding of the energy router functions and implementations.

References

[1] A. Huang, M. Crow, G. Heydt, J. Zheng, and S. Dale, "The Future Renewable Electric Energy Delivery and Management (FREEDM) System: The Energy Internet," Oct. 2010.

[2] F. Li, W. Qiao, H. Sun, H. Wan, J. Wang, Y. Xia, Z. Xu, and P. Zhang, "Smart Transmission Grid: Vision and Framework," *IEEE Transactions on Smart Grid*, vol. 1, no. 2, pp. 168–177, Sep. 2010.

[3] L. A. Barroso, H. Rudnick, F. Sensfuss, and P. Linares, "The Green Effect," *IEEE Power & Energy Magazine*, vol. 8, no. 5, pp. 22–35, Sep. 2010.

[4] R. Moreno, G. Strbac, F. Porrua, S. Mocarquer, and B. Bezerra, "Making Room for the Boom," *IEEE Power & Energy Magazine*, vol. 8, no. 5, pp. 36–46, Sep. 2010.

[5] A. Q. Huang and J. Baliga, "FREEDM System: Role of Power Electronics and Power Semiconductors in Developing an Energy Internet," in *Proc. of International Symposium on Power Semiconductor Devices*, Jun. 2009.

[6] National Institute of Standards and Technology, "NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0," *available online, http://www.nist.gov*, Jan. 2010.

[7] E. W. Gunther, A. Snyder, G. Gilchrist, and D. R. Highfill, "Smart Grid Standards Assessment and Recommendations for Adoption and Development," *available online, http://osgug.ucaiug.org*, Feb. 2009.

[8] IEEE, "1646-2004 IEEE Standard Communication Delivery Time Performance Requirements for Electric Power Substation Automation," *available online, http://ieeexplore.ieee.org*, 2005.

[9] IEC, "IEC 61850-5 Communication Networks and Systems in Substations - Part 5: Communication Requirements for Functions and Device Models," *available online, http://www.iec.ch*, Jul. 2003.

[10] Z. Xie, G. Manimaran, V. Vittal, A. G. Phadke, and V. Centeno, "An Information Architecture for Future Power Systems and Its Reliability Analysis," *IEEE Transactions on Power Systems*, vol. 17, no. 3, pp. 857–863, Aug. 2002.

[11] B. Yunus, A. Musa, H. S. Ong, A. R. Khalid, and H. Hashim, "Reliability and Availability Study on Substation Automation System based on IEC 61850," in *Proc. of IEEE International Conference on Power and Energy*, Dec. 2008.

[12] M. G. Kanabar, S. Member, and T. S. Sidhu, "Reliability and Availability Analysis of IEC 61850 Based Substation Communication Architectures," in *Proc. of IEEE Power and Energy Society General Meeting*, Jul. 2009.