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Roadmap to Smart Grid Technology: A Review of Smart Information and Communication System

Md. Ruhul Amin[1], Md. Mahmudul Hasan[2] and Rajib Baran Roy[3]

[1]Lecturer, [2]Assistant Professor, Department of Electrical and Electronic Engineering
[3]Assistant Professor, Department of Electronic and Communication Engineering
[1, 2, 3] University of Information Technology and Sciences, Dhaka-1212, Bangladesh
ruhul.amin@uits.edu.bd

Abstract

The Smart Grid, observed as the next generation power grid, uses two-way flows of electricity and information to construct a widely distributed automated energy delivery network. We investigate three major systems, explicitly the smart infrastructure system, the smart management system, and the smart protection system. In this article, we concentrate on the smart information subsystem is used to prop up information generation, modeling, integration, analysis, and optimization in the circumstance of the Smart Grid. We also propose possible future guidelines in each system. Specifically, for the smart infrastructure system, we investigate the smart information subsystem and the smart communication subsystem. We finally outline some prospect research directions and challenges.

Keywords: *Smart Metering, Phasor Measurement Unit, Cloud Computing, Wireless Mesh Network, Powerline Communications*

1. Introduction

The evolution of Smart Grid (SG) relies on not only the advancement of power equipment technology, but also the development of sophisticated computer monitoring, analysis, optimization, and control from exclusively central utility locations to the distribution and transmission grids. Many of the apprehensions of distributed automation should be addressed from an information technology perspective, such as interoperability of data exchanges and integration with existing and future devices, systems, and applications [1]. Therefore, a smart information subsystem is used to support information generation, modeling, integration, analysis, and optimization in the context of the SG. The second part in the smart infrastructure system is the smart communication subsystem. This subsystem is responsible for communication connectivity and information transmission among systems, devices, and applications in the context of the SG.

2. Smart Information System

In this section, we concentrate on the smart information and smart communication subsystem. We first explore the information metering and measurement, which generates information from end entities (*e.g.*, smarter meters, sensors, and phasor measurement units) in an SG. This information is often used for billing, grid status monitoring, and user appliance control. We then explore the information management,

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including data modeling, information analysis, integration, and optimization. We finally outline some future research directions and challenges.

2.1. Information Metering and Measurement

Study in information metering and measurement can be classified into smart metering, and smart monitoring and measurement [2]. The smart monitoring and measurement can be also divided into sensor and Phasor Measurement Unit (PMU) [3]-[5].

2.1.1. Smart Metering

Smart metering is the most important mechanism used in the SG for obtaining information from end users' devices and appliances, while also controlling the behavior of the devices. Smart meters, which support two-way communications between the meter and the central system, are similar in many aspects to Automatic Metering Infrastructure (AMI) meters, or sometimes are regarded as part of the AMI. A smart meter is usually an electrical meter that records consumption in intervals of an hour or less and sends that information at least daily back to the utility for monitoring and billing purposes [2]. Also, smart meters have the ability to disconnect-reconnect remotely and control the user appliances and devices to manage loads and demands within the future "smart-buildings." Figure 1 shows a typical usage scenario for smart meters. The smart meter collects the power consumption information of the dishwasher, TV, and the refrigerator, and also sends the control commands to them if necessary. The data generated by the smart meters in different buildings is transmitted to a data aggregator. This aggregator could be an access point or gateway. This data can be further routed to the electric utility or the distribution substation. Note that the smart communication subsystem has been described in second this paper, is responsible for the information transmission. From a consumer's perspective, smart metering offers a number of potential benefits. For example, end users are able to estimate bills and thus manage their energy consumptions to diminish bills. From a utility's viewpoint, they can use smart meters to realize real-time pricing, which tries to encourage users to reduce their demands in peak load periods, or to optimize power flows according to the information sent from demand sides.

2.1.2. Smart Monitoring and Measurement

An important function in the vision of SG is monitoring and measurement of grid status. We review the following two major monitoring and measurement approaches, namely sensors and phasor measurement units.

Sensors: Sensors or sensor networks have already been used as a monitoring and measurement approach for different purposes [6]. In order to detect mechanical failures in power grids such as conductor failures, tower collapses, hot spots, and extreme mechanical conditions, the proposed design [7] of sensor networks should be embedded into the power grid and help to assess the real-time mechanical and electrical conditions of transmission lines, obtain a complete physical and electrical picture of the power system in real time, diagnose imminent as well as permanent faults, and determine appropriate control measures that could be automatically taken and/or suggested to the system operators once an extreme mechanical condition appears in a transmission line. Wireless sensor networks (WSNs) in particular, given their low cost, can provide a feasible and cost-effective sensing and communication platform for remote system monitoring and diagnosis. The application of WSNs for electric power systems along with their opportunities and challenges and presented a comprehensive experimental study in different electric power system environments [8]. They concluded that with the support of WSN, a single system contingency in the power grid could be spotted and isolated before it causes cascading effects and leads to more disastrous system-wide interruptions.

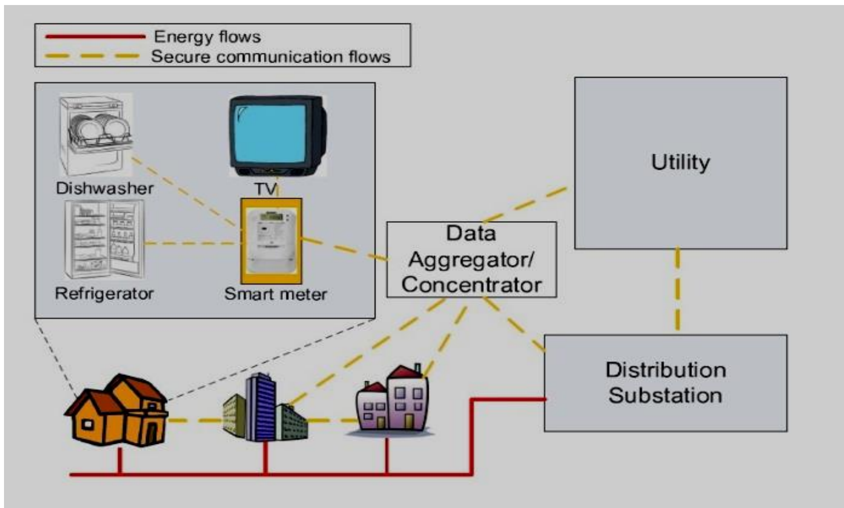

Figure 1. An Example of the Smart Metering Structure

However, the use of sensor networks in the SG has many requirements [8-9]:

- Quality-of-Service (QoS) requirements: The information generated by sensor networks may be associated with some data QoS requirements, such as reliability, latency and network throughput. For example, the critical sensed data related to grid failures should be received by the controller in a timely manner. The communication subsystem supporting sensor networks must provide mechanisms to satisfy these QoS requirements.
- Resource constraints: Sensor nodes are often low cost and resource limited devices. Thus the control programs for sensor networks should be energy efficient.
- Remote maintenance and configuration: Sensors must be remotely accessible and configurable, so that the sensor networks could be maintained remotely, conveniently and promptly.
- High security requirements: Security is very important for electric power systems. By compromising sensors, attackers can jeopardize the power grid operation.
- Harsh environmental conditions: In SG environments, sensors may be subject to radio frequency (RF) interference, highly caustic or corrosive environments, high humidity levels, vibrations, dirt and dust, or other conditions that may cause a portion of sensor nodes to failure. Hence the sensor network design

must consider the survivability requirement, *i.e.*, the sensor network is still connected or the critical areas are still monitored if some sensors fail.

Phasor Measurement Unit: Recent developments in the SG have laid interest in the use of phasor measurement units (PMUs) to help create a reliable power transmission and distribution infrastructure [10]. A PMU measures the electrical waves on an electrical grid to determine the health of the system. Technically speaking, a phasor is a complex number that represents both the magnitude and phase angle of the sine waves found in electricity. Phasor measurements that occur at the same time are called synchrophasor, as are the PMU devices that allow their measurement. Typically, PMU readings are obtained from widely dispersed locations in a power system network and synchronized using the global positioning system (GPS) radio clock. With a large number of PMUs and the ability to compare shapes from alternating current (AC) readings everywhere on the grid, system operators can use the sampled data to measure the state of the power system and respond to system conditions in a rapid and dynamic fashion [11].

Early research on the applications of PMU technology was mainly focused on validation of system models and accurate post-mortem analysis. However, now with wide-scale real-time PMU data being obtainable, system operators have the capability of deploying system state estimation procedures and system protection functionalities in power grids, with the goal of making the power system invulnerable to catastrophic failures. Several countries, such as Brazil, China, France, Japan, South Korea, Mexico, Norway, the U.S. and some area in India, have installed PMUs on their power grid systems for research or are developing prototypes [12]. The installation of PMUs on transmission grids of most major power systems has become an important activity. In addition, the investigation of PMUs is an exciting part being explored by both industry and academia. Industry is investigating how to install the PMUs, collect the data, and establish communication transfers of this data to the utility control centres [13]. In academia, typical research fields are the applications of PMU for grid protection functions, such as providing loss-of-mains protection [14], monitoring fault event [15], locating disturbance [16], estimating grid state [17], studying synchronous islanded operation, monitoring power quality, and devising experimental applications for the monitoring of active distribution grids [18].

2.2. Information Management

In SG, a large amount of data and information will be generated from metering, sensing, monitoring *etc*. SG must support advanced information management. The task of the information management is data modeling, information analysis, integration and optimization.

2.2.1. Data Modeling

As stated by IEEE P2030 [109], the goal of SG information technology data modeling is to provide a guide to creating persistent, displayable, compatible, transferable, and editable data representation for use within the emerging SG. In other words, the objective is to make it as interoperable as possible using relevant standards. That is specifically addressing the data that represents state information about the grid and individual items in it. This would include nearly all connected items from generation down to individual consuming devices. They all have state information that may need to be read, stored, transmitted etc. Why is data modeling important? Let us look at the following two reasons. First, the information exchange between two application elements is meaningful only when both of them can use the information exchanged to perform their respective tasks. Therefore, the structure and meaning of the exchanged information must be understood by both application elements. Second, the data modeling is also related to the system forward compatibility and backward compatibility. On one hand, a well-defined data model should make legacy program adjustments easier.

2.2.2. Information Analysis, Integration and Optimization

Information analysis is required to support the processing, interpretation and correlation of the flood of new grid observations, since the widely deployed metering and monitoring systems in SG will generate a large amount of data for the utility. One part of the analytics would be performed by existing applications, and another part of the analytics dimension is with new applications and the ability of engineers to use a workbench to create their customized analytics dashboard in a self-service model [1]. Information integration aims at the merging of information from different sources with different conceptual, contextual and typographical representations. In SG, a large amount of information has to be integrated. First, the data generated by new components enabled in SG may be integrated into the existing applications and metadata stored in legacy systems may also be used by new applications in SG to provide new interpretations. IEEE P2030 [1] indicated that data integrity and name services must be considered in information integration. Data integrity includes verification and cross-correlation of information for validity and designation of authoritative sources and who are responsible for specific personnel who own the data. Name service addresses the common issue of an asset having multiple names in multiple systems. Second, presently most utility companies have limited installed capability for integration across the applications associated with system planning, power delivery and customer operations. In most cases, this information in each department is not easily accessible by applications and users in other departments or organizations. These “islands of information” correspond to islands of autonomous business activities. Therefore, the emerging SG calls for enterprise level integration of these islands to progress and optimize information utilization throughout the organization.

Information optimization is used to improve information effectiveness. The data size in the future SG is anticipated to be fairly large as a result of the large-scale monitoring, sensing and measurement. However, the generated data may have a large amount of redundant or useless data. Therefore, the advanced information technology is required to improve the information effectiveness, in order to reduce communication burden and store only useful information. In order to compress the size of disturbance signals and reduce sinusoidal and white noise in the signals, a wavelet-based data compression approach has been proposed for SG [19].

2.3. Future Research on Smart Information System

In this section, the work on the smart information subsystem has been reviewed, especially information metering, measurement and management in SG. Then the following challenges and possible directions worth exploring are enlisted.

- Effective information store: A large amount of information, such as the data from smart meters, sensors and PMUs will be sampled in SG and sent to the control system. One vital problem is what information should be stored in the control system so that meaningful system or user history can be constructed from this data. Note that system history is important for analysing system operations and user history is important for analysing user behaviours and bills.
- The utilization of cloud computing: Cloud computing has been intended as the next-generation computing paradigm for its major advantages in on-demand self-service, universal network access, location independent resource pooling and transference of risk [20]. The basic idea of the cloud computing is that the cloud providers, who operate large data centres with enormous computation and storage capacities, deliver computing as a service, whereby shared resources, software and information are provided to computers and other devices as a utility over a network. Integrating cloud computing may improve the information management in SG. First, since cloud providers have massive computation and storage capacities, they can design some basic and generic information management services for electric utilities. Second, cloud computing may be able to improve the information integration level in SG.

3. Smart Communication System

The second part in this paper is the smart communication subsystem of SG Technology. This subsystem is responsible for communication connectivity and information transmission among systems, devices and applications in the context of the SG. In this section, the smart communication subsystem in SG has been overviewed. Then the wireless and wired communication technologies are discussed subsequently. Figure 2 shows an example of a communication network used in SG. User devices and smart meters use ZigBee, Wi-Fi, and powerline communications. Wireless mesh networks are used for information exchanges between users. Communities are connected to their electric utility via free-space optical, satellite, microwave, or cellular systems. A substation communicates with an electric utility over the powerline.

3.1. Wireless Technologies

Wireless technologies not only offer significant benefits over wired technologies, such as low installation cost, rapid deployment, mobility, *etc.*, but are also more suitable for remote end applications. Wireless has already been widely used in our daily life and can be deployed anywhere and anytime. The following important wireless communication and networking technologies may be applicable in future SG.

3.1.1. Wireless Mesh Network

Wireless mesh network (WMN), which is a communication network made up of radio nodes organized in a mesh topology, has developed as a key technology for next-generation wireless networking. Industrial standards groups, such as IEEE 802.11 and 802.16 are all actively working on new specifications for WMNs. A WMN also offers basic networking infrastructure for the communications in SG. Some of the benefits of using WMNs in SG are highlighted as follows:

- *Increased communication reliability and automatic network connectivity*: Since redundant paths usually exist in WMNs, network robustness against potential problems, *e.g.*, node failures and path failures can be improved. Furthermore, generally speaking a WMN is self-organized and self-configured. This feature is crucial for electric system automation, since it enables electric utilities to cope with new connectivity requirements driven by customer demands [21].
- *Large coverage and high data rate*: Wi-MAX mesh network can be able both long distance and high data rate communications. In the SG, a large amount of data, such as the information from smart meters, sensors, and phasor measurement units (PMUs), will be generated and sent to the control system. A communication network with large coverage and high data rate is necessary.

Recently, some researchers have conducted some studies along this line. Multi-gate mesh network architecture is proposed to handle real-time traffic for the last mile communication. The multi-gate routing is based on a flexible mesh network architecture that expands on the hybrid tree routing of the IEEE 802.11s. The network is specifically designed to operate in a multi-gateway structure in order to meet the SG requirements in terms of reliability, self-healing and throughput performance [22].

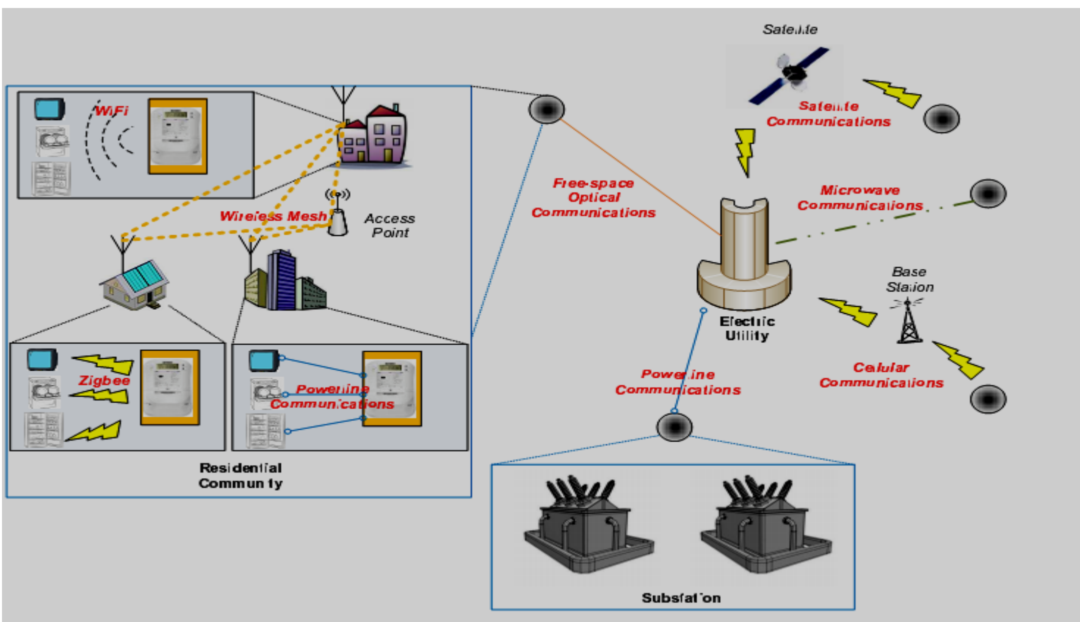

Figure 2. An Example of a Communication Network used in SG

3.1.2. Cellular Communication Systems

A cellular communication system, such as GSM and 3G (WCDMA and CDMA-2000), is a radio network distributed over land areas called cells, each served by at least one fixed-location transceiver known as a cell site or base station. It has been a proven mature technology for data transmission for several decades. By using the existing 3G (or even 4G) cellular communication systems, it is quick and inexpensive to obtain data communications coverage over a large geographic area [23].Researchers have also conducted some studies on cellular communications for the SG. For example, a new network model in which sensor/relay nodes can also communicate with other back-end nodes using a wide area network such as the cellular network, and proved that the delay and cost of transmitting data can be reduced [24].

3.1.3. Cognitive Radio

The communication system in SG needs to be designed to accommodate the current management requirements as well as the potential demand of future applications. It is likely that unlicensed spectrum will also be used when SG is in large-scale commercial use.

3.1.4. Communications based on 802.15.4

Three wireless communication technologies based on IEEE 802.15.4 protocol stack are recommended to be used in SG [23]. Which are ZigBee, Wireless HART, and ISA100.11a. ZigBee is a wireless technology which is planned for radio-frequency applications that require a low data rate, long battery life and secure networking.

3.1.5. Satellite Communications

Satellite communication is a good solution for remote control and monitoring, since it delivers global coverage and rapid installation [21]. In some scenarios where no communication infrastructure exists, especially for remote substations and generation deployments, satellite communication is a cost-effective solution. However, it would be noted the disadvantages of satellite communications. There are two major limitations. First, a satellite communication system has a substantially higher delay than that of a terrestrial communication system. This makes some protocols (*e.g.*, TCP), which are originally designed for terrestrial communication, unsuitable for satellite communications [8]. Second, satellite channel characteristics vary depending on the effect of fading and the weather conditions. This property can heavily degrade the performance of the whole satellite communication system [25].

3.1.6. Microwave or Free-space Optical Communications

Microwave technologies are widely used for point-to-point communications, since their small wavelength allows use of conveniently sized directional antennas to obtain secure information transmission at high bandwidths. Free-space optical communication is an optical communication technology that can use light broadcasting in free space to transmit point-to-point data. It allows high bit rates with low bit error rates. Furthermore, it is very secure due to the high directionality and narrowness of the beams. In addition to providing long-distance point-to-point communication in remote or rural areas, these “optical wireless” technologies also provide point-to-point solutions suitable for use in dense urban areas where microwave solutions are impractical from an interference standpoint. Therefore, one important application of microwave or free-space optical point-to-point communications is to build up SG communication backhaul networks. This is especially important in rural or remote areas, where using other wireless or wired technologies is costly or even impossible. However, both microwave communication and free-space optical communication are line of sight (LOS) communication technologies. Therefore, their communication qualities are greatly affected by obstacles (*e.g.*, buildings and hills) and environmental constraints (*e.g.*, rain fade).

3.2. Wired Technologies

It is also assumed that wired communication technologies would be integrated into SG. The important wired communication technologies are given below.

3.2.1. Fiber-optic Communications

Due to its high bandwidth capacity and invulnerability characteristics, it is supposed that optical fibers would play an important role for the information network backbones in future SG [8]. Although it is well-known that the installment cost of optical fibers may be expensive, fiber optic network is still a cost-effective communication infrastructure for high speed communication network backbones in future SG, since such fibers are already widely deployed in today's communication network backbones, with a large amount of spare capacity being unused.

Powerline Communications: Powerline communications (PLC) is a technology for carrying data on a conductor also used for electric power transmission. In the last decades, utility companies around the world have been using PLC for remote metering and load control applications. The debate on what is the actual role of PLC in future SG is still open. Some advocate that PLC is very good candidates for some applications, while others express concerns on PLC (*e.g.*, the security issue due to the nature of powerlines) [26]. Although the SG could use many different communications technologies, without a doubt, PLC is the only wired technology that has deployment cost comparable to wireless technologies since the lines are already there.

3.3. End-to-end Communication Management

One important issue in the communication subsystem is the end-to-end communication management. More specifically, in this heterogeneous communication subsystem where various communication technologies, network structures, and devices can be used, it is required to identify each entity and solve the problem of how to manage end-to-end communications. Recently, there is a growing trend towards the use of TCP/IP technology as a common and consistent approach in order to achieve end-to-end communications [27]. National Institute of Standards Technology (NIST) also indicated that there are a number of benefits that make TCP/IP an important SG technology, including the maturity of a large number of standards, the availability of tools and applications that can be applied to SG environments and its widespread use in both private and public networks [28].

3.4. Future Research on Smart Communication System

In this section, the work on the smart communication subsystem, including wireless technologies, wired technologies and end-to-end communication management are reviewed consequently. The challenges and possible directions worth exploring of smart communication system are also enlisted.

- Interoperability of communication technologies: Since many different communication protocols and technologies would be advised in SG and each of them probably can be its own protocols and algorithms, materializing interoperability is not easy. Although the framework architecture in the classic layer model of Open Systems Interconnection could provide a promising conceptual solution to this problem, it is well-known that this model suffers in some modern applications.

- Dynamics of the communication subsystem: The communication subsystem underlying an SG can be dynamic, with topology changes being unpredictable. For example, both the operation of connecting (or disconnecting) the electric vehicle (EV) to (or from) the grid and the motion of vehicle may result in the change of communication network topology.

- Smoothly updating existing protocols: The current power grid has used several protocols to realize simple data communications. For example, the currently used metering and Supervisory Control and Data Acquisition Systems (SCADA protocols are based on a simple request/response scheme with their own addressing [27]. One problem is how to smoothly update existing protocols to the ones which are applicable in future SG.

4. Conclusions

SG is a complex system of systems, resulting in complicated interactions among energy, information and communication subsystems. The evolution of the SG infrastructure may ask for more experienced information and communication technology sectors to be involved. It would be suggested using data mining, machine learning, and information retrieval techniques to analyze the information and thus obtain the representative data. The cloud computing may improve the information management in SG, it also carriages many challenges. First, information security and privacy must be the major concern of electric utilities, since the information storage and management is out of the control of electric utilities. Second, it is unlikely that an electric utility outsources all the information management functions to the cloud. The performance of the pure TCP may be very bad in wireless networks since it cannot differentiate packet loss due to wireless fading from that due to a real congestion in the network. In order to improve the quality of service, under various operational conditions, some functions or services are not tied to a given layer, but can affect more than one layer. First, systematic protocol designs are needed to support topology dynamics. For example, communication protocols should be compact with topology reconfiguration in the connect-disconnect operation of EVs. Second, dynamic resource allocation algorithms are needed to support topology dynamics. For instance, due to the topology change, the network resources (*e.g.*, bandwidth) may need to be reallocated to optimize performance. To smoothly transit the systems using these protocols to the ones applicable in future SG is still an open question. For this open question, it can be able to borrow from industry the idea of how to smoothly update old IPv4 networks to new IPv6 networks. This transition can be done in two stages: 1) the system can communicate using pre-existing old protocols and also TCP/IP and 2) the system operates by only using TCP/IP. A complete solution along this line is desired.

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Authors

Md. Ruhul Amin, he has been working as a Lecturer at the Department of Electrical and Electronic Engineering in the University of Information Technology & Sciences (UITS), Dhaka, Bangladesh since January 2013. He holds a Bachelor of Science degree in Electrical and Electronic Engineering with specialization on Power Systems Engineering from UITS'2012, Dhaka. He has several national and international publications in his area of expertise. His research area addresses the issues related to Electrical Power System and Engineering; FACTS, Distributed Generation and Control; HVDC; Renewable Energy; Smart Grid; Power Electronics.

Md. Mahmudul Hasan, has been an Asst. Professor at University of Information Technology & Sciences, Dhaka, Bangladesh since 2010 and before that he was an Asst. Professor at KIIT University since 2009. He holds a Masters of Technology degree in Electronics and Telecommunication with specialization on Communication Systems Engineering, and a Bachelor of Technology degree in Electronics and Telecommunication Engineering from KIIT University, India. He has several national and international publications in his area of expertise. His research area addresses the issues related to wireless communication and network; WLAN, multicarrier and multiuser communications like CDMA, OFDM, MIMO; Wireless sensor networks; Smart Grid and Microstrip antenna.

Rajib Baran Roy, he has completed Bachelor of Science in Electrical Electronic Engineering from Chittagong University of Engineering and Technology (CUET), Chittagong, Bangladesh and Master's of Science in Sustainable Energy System and Management from University of Flensburg, Germany. He is currently working as an Assistant Professor in the Electrical and Electronic Engineering department of the University of Information Technology and Sciences (UITS), Dhaka, Bangladesh. So far he has five publications in international journals. His research interests are electrical power system analysis, reactive power compensation, hybrid power system, and renewable energy based distributed power system and application of industrial electronics in power system.