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TOPICAL REVIEW

Exploring the Potential Application of IEC 61850 to Enable Energy Interconnectivity in Smart Grid Systems

NAROTTAM DAS[1,2], (Senior Member, IEEE), AKRAMUL HAQUE[3,4], HASNEEN ZAMAN[1], SAYIDUL MORSALIN[5], (Member, IEEE), AND SYED ISLAM[6], (Life Fellow, IEEE)

[1]School of Engineering and Technology, Central Queensland University, Melbourne, VIC 3000, Australia
[2]Centre for Intelligent Systems, Central Queensland University, Brisbane, QLD 4000, Australia
[3]School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, Wollongong, NSW 2522, Australia
[4]Department of Electrical and Electronic Engineering, Premier University, Chittagong 4367, Bangladesh
[5]School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney, NSW 2052, Australia
[6]School of Engineering, Information Technology and Physical Sciences, Federation University Australia, Ballarat, VIC 3352, Australia

Corresponding authors: Narottam Das (n.das@cqu.edu.au) and Akramul Haque (akramul073@gmail.com)

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ABSTRACT In the quest of an efficient smart energy management system that can fulfill the power demand of consumers, researchers are focusing on smart power system which can integrate both conventional and renewable energy resources as well as production of clean energy. As a result, the concept of Internet of Energy (IoE) is developed which is similar to the perception of Internet of Things (IoT), which supports both energy and information flow. In this study, a systematic review of the current state-of-the-art of IoE and IEC 61850 has been presented, and it has identified the research gaps and opportunities for future development. The discussion unfolds by illuminating the evolution of smart grids and IoE, shedding light on the benefits and challenges inherent in employing IEC 61850 as a communication standard for IoE. Moreover, the potential application of IEC 61850 standard for enabling IoE in smart grids has been explored. Besides reviewing the trends and challenges of IoE and its key technologies, such as energy routers, power generation equipment, and energy storage devices; it also discussed how the IEC 61850 standard can facilitate the communication and interoperability among these technologies and provide a robust and flexible platform for the IoE. The outcome of this study show that IEC 61850 has a wide range of applicability and suitability for IoE, as it can support various functions and features of IoE, such as information modeling, data exchange, plug-and-play, fault detection, and intelligent control. This study also presents some examples of IEC 61850 based IoE systems, such as energy routers, wind and solar power plants, battery storage systems, and vehicle-to-grid systems. The comparison of this study with the equivalent studies shows that this study provides a comprehensive and up-to-date overview of IoE and IEC 61850, and covers a wide range of topics and aspects of IoE and IEC 61850. This study also provides a critical evaluation of the strengths and weaknesses of IEC 61850 for IoE, and proposes some directions for future research and development.

INDEX TERMS DER, IEC 61850, IED, IoE, IoT, energy router, GOOSE, smart grid.

I. INTRODUCTION

The present electricity network is going through a revolutionary shift towards achieving smart grid goal because of distributed energy resources (DERs) and renewable energy sources (such as, wind, solar, hydro and others), and as a consequence, we as consumers or prosumers will tend to rely on smart grid for our electricity needs [1], [2]. However, the execution of distributed energy management (DEM) in real time along with automation becomes a constraint on the way to

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establishing a smart power system [3], [4]. The prime objective of DEM is to provide optimal and safe operating points (usually power and voltage) for the controller of each DER to meet the electrical load demands, increase operational efficiency of the grid, lessen emissions and losses, and provide fast and stable fault tolerance abilities or faster islanding during grid faults if necessary [5], [6], [7]. Energy management in conventional power network is achieved through the controlled operation of power electronics at the DERs site. Droop controllers are also used to regulate real and apparent power for the case of integrating several DERs connected with each other to parallel [8]. However, droop control is found to be inefficient for non-linear loads, especially for the case when frequency and voltage control are likely to be load dependent etc. [9]. Therefore, a layer of hierarchical or secondary control in addition to droop control is must to avoid the drawbacks of droop controllers. Hierarchical control is only possible when a coordinated information management (IM) is implemented in real time in order to establish lower latent and higher efficient communication between central controller and the local controller of each DER.

To this aim, the electric power industry is going through a period of a major shift in the use of advanced communication technology in an effort to develop a smarter grid that can successfully meet the challenges of today and the future. This causes the traditional power system to see a paradigm movement towards internet of energy (IoE) where both information and power flow are parallel each to other. This is a big leap for power industry, as the smart grid is now transforming to virtual power plants (VPP) and virtual energy storage systems [10]. The IoE can also play a significant role in operation of power systems, microgrid, integration of renewable resources, demand response, integration of electric vehicle with V2G capability, and smart buildings, etc. [11]. IoE also has the potential to contribute to the concept of smart cities which focuses on improving public services, such as intelligent monitoring and management of transportation systems, healthcare services, and structural health monitoring (SHM) systems, etc. [12].

In the effort of standardizing information flow towards IoE automation, IEC 61850 is emerging as one of the most promising solutions for managing DERs. Due to its interoperable capabilities, this standardized system is gaining popularity in many countries and has also been identified as one of the cardinal technologies for future smart grid applications. The main goal of IEC 61850 is to contribute as a communication protocol to overcome multivendor interoperability issues in substations. Several works have been published and reviewed covering the potential of IEC 61850 to model substation equipment. Extensive survey of literatures focused on message exchange formats for substation functionalities, feasibility of various network architectures to analyze latency and other network evaluation parameters has been done [13]. Previous studies provide more or less oriented data modeling of IEC 61850 but were limited to include DERs integration into the IoE platform. As per IEC 61850 guidelines, Apostolov et al. reported data models of distributed resources [14] and Ustun et al. presented relevant communication modeling for a centralized protection system [15]. Grid integration of wind energy using IEC 61850 was discussed in [16] and outlined a simplified energy management system for both coordination and control of distributed resources [17]. However, the above studies were inadequate in evaluating dynamic performance of modeled communication in terms of network topology, message size, end-to-end delay etc. To understand both implications and applications of IEC 61850 in smart grid environment, it is highly required to identify the relevant features (i.e., interfaces, components, and performance) of smart DEM systems towards IoE.

This paper illustrates the preliminary requirements of implementing IEC 61850 application in managing distributed resources. It can assist research communities and engineers who are involved in IoE related developments and make their first steps in understanding the concepts and suitability of the standard to incorporate DES with the smart grid. The primary focus is to make the detailed understanding about the applicability of IEC 61850 standard in a DEM system so that a robust, deterministic and interoperable communication system can be realized towards IoE trends in power system networks.

The main contribution of this paper is to review the trends and challenges of IoE in smart grids and to explore the potential application of IEC 61850 standard for enabling IoE. Some of the main key points are listed below:

- IoE is an emerging concept that integrates the Internet of Things (IoT) with the smart grid for developing a more efficient and interconnected power/energy network system that supports both energy flow and information flow.
- This paper discusses the applicability of IEC 61850 for some of the main features of the IoE framework, such as energy routers, power generation equipment, and energy storage devices. It also reviews some of the existing research works that have used IEC 61850 for modeling, controlling, and communicating with these components.
- It also identifies some of the research gaps and limitations of IEC 61850 for IoE and suggests some possible solutions, such as using middleware technology, extending the information model, and integrating other standards.

This paper is outlined as follows: section I is Introduction, II presented the related works, while IoE has discussed in section III. An overview of IEC 61850 and IoE have been presented in section IV and V respectively. The key technologies of IoE have been discussed in sections VI-VIII with drawing the conclusion in section IX.

II. RELATED WORKS

IEC 61850 is an international standard which facilitates various services of the substation automation and smart grid application, by defining the communication architecture with common data model. Scalability, security and ensuring interoperability among different devices are the main advantages of implementing IEC 61850. Many researchers are working to explore the potential application of IEC 61850 in smart grid.

Docquier et al. has proposed a tutorial introduction to the present IEC 61850 standard and evaluated the switched Ethernet based automated substation network performance. They analyzed the performance not only by simulation approaches but also using network calculus [18]. Moreover, two advanced features: simulation and subscription, of IEC 61850 edition 2 have been implemented by Kariyawasam et al. where they tested those features for protection devices specially for a distance protection relay [19]. They conclude that these features are flexible and convenient for carrying out tests in substation automation systems. To provide the easy interaction with the smart grid data without any prior knowledge of IEC 61850, a web platform has been developed [20]. It helps to map the IEC 61850 models into Message Queue Telemetry Transport (MQTT) messages. Moreover, the idea of next-generation smart grid driven by artificial intelligence and leveraged by IoT and 5G has been properly discussed by Esenogho et al. [21].

Recognizing the need for a platform that adheres to IEC 61850 standards, a modified Open PLC (Programmable Logic Controller) was developed for emulation purposes [22]. Authors implemented the OpenPLC61850 to measure the impacts of cyber-attacks and the response of PLC control logic. Among various types of cyber-attacks, the false data injection has not been extensively analyzed. Hence, Roomi et al., implemented a virtual smart grid testbed incorporating IEC 61850 standards and observed the impacts of false data injection in generator side [23]. As a solution they proposed an efficient message authentication system to alleviate the identified attack vector and found 16% latency improvement compared to the existing system. A comprehensive review on legacy protocols used in substation system has been discussed by Kumar et al. [24]. Though the advantages and disadvantages of traditional protocols were discussed but applicability in case of power generation equipment and energy storage devices were not illustrated. Saadi et al. has examined the performance of the Generic Object Oriented Substation Event (GOOSE) communication, which is a fast and reliable mechanism for data exchange in IEC 61850 in substation automation system [25]. Moreover, a secured GOOSE communication framework for sending synchro phasors data in a smart grid was deployed [26]. The main focus was synchro phasors data security for proper operation of substation monitoring and controlling. A systematic review of GOOSE messages has also been done by Silveira et al. [27], machine learning based intrusion detection was reviewed in [28].

In summary, the importance of studying the potential application of IEC 61850 in the context of the IoE lies in the foundational understanding, optimization of features, development of practical tools, and the enhancement of cybersecurity measures, all of which are crucial for the successful implementation and evolution of smart grids.

III. INTERNET OF ENERGY

This section describes in brief about the IoE and its application in smart network. The IoE is an emerging concept to integrate the Internet of Things (IoT) with the smart grid for developing a more efficient and interconnected energy system that supports both energy flow and information flow [29]. A schematic diagram of IoE infrastructure incorporating with IEC 61850 is shown in Fig. 1. The energy flow is shown in the lower portion of the Fig. 1 which constitutes various DESs and EVs, while the upper portion shows only the information flow.

The incorporation of IoE in Smart grid can be beneficiary in many ways including the enhancement of the performance, reliability, and sustainability of the power system. Depending on the availability of the energy and the instantaneous energy cost, IoT enables the utility company to adjust the energy consumption [11]. Consumers can know the real time pricing of the energy using IoE and receive incentives by shifting their demand in off-peak hour [30].

The integration and management of various DESs, for example: wind turbines, solar panels and battery storage systems can be facilitated using IoE. The IoE can enhance the operation of these distributed resources using various algorithms. For optimum operation of energy networks, a hierarchical control needs to be implemented in an IoE system, which is ideally realized by four control schemes at different levels.

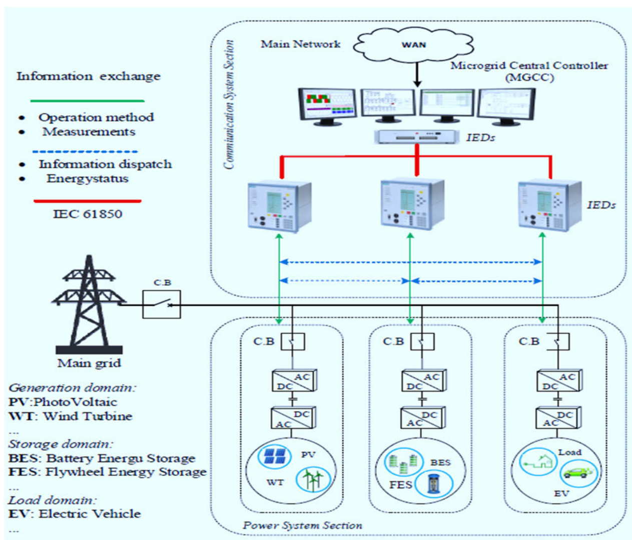

FIGURE 1. A simple functional block diagram of IoE architecture [31].

The inner loop-level control is responsible for processing, the primary-level is responsible for sensing and measuring, the secondary-level is responsible for monitoring and decision-making and finally, the tertiary-level is highly required for optimized maintenance and elevated performance [32].

With conventional communication topology, the Supervisory Control and Data Acquisition systems (SCADAs) or DEMs find it difficult to maintain large number of devices and power apparatus and apply correct control methodology for their reliable operation [33]. On the other hand, delivering power to the consumer end while maintaining maximum quality is also challenging and a rapid intelligent control system is highly required in IoE architecture [34]. From information flow perspectives, the IoE system thereby requires supporting a rapid information exchange feature and 'plug-and-play' functions. The hierarchy of information exchange comprises into station, bay, and process level data transfers. It should be noted that the IEC 61850 includes information exchange and data transfer between the bay and station levels [35]. For managing distributed energy resources, IEC Technical Committee 57 (TC57) extends the IEC 61850 scopes and the IEC 61850-7-420 was documented for monitoring, measuring and controlling DERs at hierarchical level [36].

IV. IEC 61850 OVERVIEW

A smart DEM in IoE framework includes a secondary control method-based communication interfaces among multiple agents and a tertiary control among intelligent agents to optimize performance [37]. As described earlier, for IoE operation, the functions of IEC 61850 can be divided into three levels, which are described as follows [38], [39], and [40]:

a) Process level: The process level has all switchgear equipment, such as Current Transformers and Potential Transformers (CTs, PTs), Circuit Breakers (CBs) etc. This level is directly connected to the power system and power electronic devices, for an example AC-DC converter. The responsibilities of this level are:

1) To be able to collect system data and send it to bay level.
2) To manage the connection between the main grid and distributed energy resources.
3) To send the value of voltage and frequency to avoid possible hazards.

b) Bay level: The bay level is responsible for monitoring, supervising, and controlling the system. It receives data from the process level and sends it to the station level after controlling it using intelligent electronic devices (IEDs). The functions of this level are:

1) To maintain balance between electricity generation and consumption.
2) To ensure the security of the power system by analyzing the data received from process level.
3) Monitoring the power in accordance with operating condition.

c) Station level: This level contains the Human–Machine Interface (HMI) and SCADA systems. This level collects data from different bays and provides data exchange between the bay and station level [41]. The tasks of this level are:

1) To perform the overall controlling and monitoring of the whole system.
2) To communicate with remote network control center.
3) To communicate with bay controllers through the station bus.

The station, process and bay level are connected to each other by two buses- process bus and station bus [42]. In the process level, communication within the devices is achieved by process bus using sampled value (SV) messages and GOOSE message [43]. The overall logical interface of the substation automation system has been shown in Fig. 2.

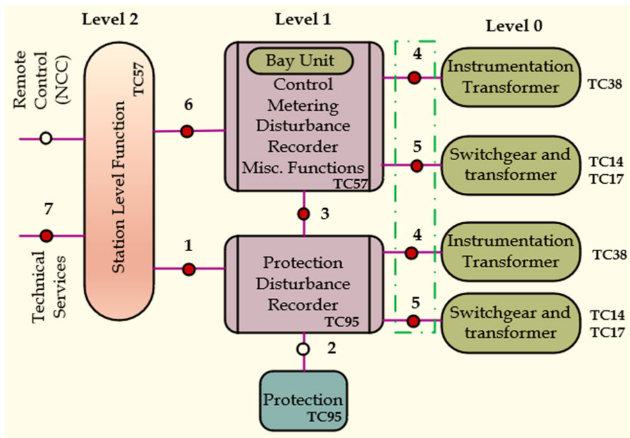

FIGURE 2. The rational linking of the substation automation system.

In IEC 61850, the basic element of IED is 'Logical Devices (LD)' which contains 'Logical Nodes (LN)' [44]. All the LNs and LDs in IEC 61850 are developed in the context of power system functions, such as protection relay, circuit breaker, power electronics, etc. The LNs have been explained in the IEC 61850-7-4. mentioning the first letter in the name of each LD shows the type of equipment [45]. For instance, X is used for the switchgear section and XCBR is a circuit breaker [46].

V. IEC 61850 IN INTERNET OF ENERGY

This section describes the application of IEC 61850 for IoE in smart grids (SG) and other applications as well. IEC 61850 is stated as one of the significant IoE platforms building blocks towards developing the SG [47]. This standard can help the IoE for control and supervision of LDs which are essential parts of the convergent SG goal [48]. The IoE with the support of IEC 61850 can endorse interoperability among various renewable energy sources and devices. For example, it facilitates the data exchange among PV farm, wind farm, electric vehicles (EVs), and different energy storage systems by following standardized communication infrastructure for better efficiency and the system reliability.

Integrating IEC 61850 with IoE can render real-time energy production, consumption, and distribution data for which the utilities can take intelligent decisions promptly. Besides, by implementing various IoT devices in home buildings, IoE techniques or system can reduce the energy cost significantly. Moreover, IoE facilitates the peer-to-peer energy trading between consumers and utility companies directly that boosts the transparency as well as efficiency of the energy market. An IoE integrated smart grid facilitates the implementation and communication among multidisciplinary sectors such as: agriculture, transportation, health etc. A simplified diagram of a smart grid with IoE has been shown in Fig. 3.

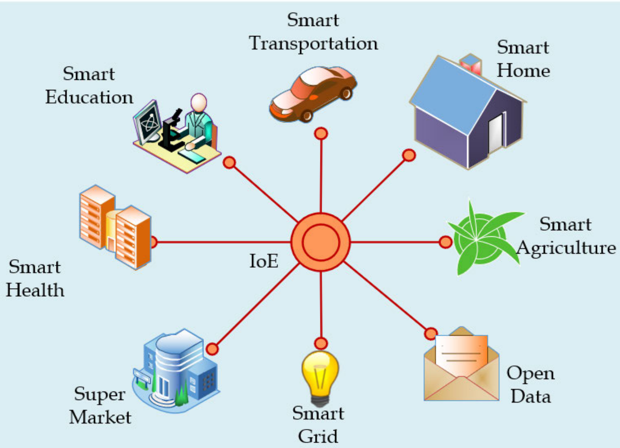

FIGURE 3. An IoE integrated smart grid system configuration.

However, some parts of the IEC 61850 system definitions are insufficient to cope with the accelerated SG evolution process [49]. Therefore, a middleware technology is required to fill the gap in IEC 61850 systems [47]. Some research works have been recently carried out to develop the automation and control system of future SG combining IEC 61850 with other standards, like Open Platform Communications United Architecture (OPC UA) [47]. Moreover, the applicability of the IEC 61850 standard has been tested in developing the main features of IoE framework, such as, energy router (ER), power generation and storage devices etc. [50], [51], [52], [53], [54], [55], [56], [57], [58]. Large scale deployment of diverse power grid actors with capability of bidirectional flow of energy and information has provided unforeseen ecology of prosumers (i.e., Smart Grid entities those are both the producers and consumers of electricity), such as EVs, smart houses, and smart buildings/ offices. Along with escalating the number of integrated DERs and smart meters, prosumers define pervasive smart grid environments, i.e., electric power grids with the capability to fully utilize SG benefits, such as optimal power flow, self-healing network ability or economic dispatch of energy.

Divergent characteristics of entities included in pervasive SG environments require the existence of a universal approach for remote control and supervision of field devices in order to enable their optimized management. The IoE is envisioned as an overlay network for electric power grid, fulfilling these requirements [8]. The IoE is defined as a combination of Smart grid entities that share common methodologies for addressing, modeling, and exchanging information among devices and applications. However, the IoE requires concrete technical solutions that fulfill the aforementioned requirements in a technology-neutral and vendor-independent manner.

VI. KEY TECHNOLOGIES OF IoE: ENERGY ROUTERS

Energy Router (ER) is the building block of IoE and it is assumed to be a crucial element of future smart power systems [59]. This is due to their ability to provide multidirectional power flow [53]. The ER can also maintain smart power flow between IoE and utility [60]. Therefore, the ER is an indispensable part of smart grid to maintain communication between power devices [61].

A. BASIC STRUCTURE OF ENERGY ROUTERS

ER primarily controls the power flow between AC and DC buses between two or more layers of a smart power system [57]. A layout of single ER is shown in Fig. 4. It consists of a common DC bus, multiple input and output ports of AC/DC or DC/AC modules, energy storage devices and energy routing controller (ERC) [53].

The common DC bus is a regulated bus which is used to connect end-users and it acts as a medium of power exchange and it can also maintain power balance for a short period of time [53], [62]. Besides the local grid, the DER plants are also connected at the input ports. The AC, DC loads and storage devices (SDs) are connected at the output ports. Any power electronic devices having similar or different power ratings can be connected to these ports. The stability, robustness, and efficiency of the system are maintained by using a standard interface for interconnecting devices [63].

The control of ER is accomplished by an intelligent control module, which mainly supervises the parameters of the power electronic converters and switches [64], [65]. This module collects and analyses the information collected from power lines, distribution system operator (DSO), distributed generators (DG) and manages to supply power where it is in maximum demand. An ER can exchange power with another ER and can store excess energy or send it back to the power grid.

B. FUNCTIONS OF ENERGY ROUTERS

Primarily, an ER is designed to exchange power and information between IoE and main power grid [66]. Therefore, the performance of energy router is crucial for efficient use of DER equipment, maintaining the balance of IoE, and providing a strong support for the main power grid [52]. The main functions of an ER can be summarized as follows [52], [61], [67], [68]:

1) Achieving balance between power supply and demand within IoE by calculating power flow from power generation and analyzing the feedback from consumers and sensors in power plant. As a result, both grid and prosumers can access efficient power sharing options.
2) An ER has to ensure flexible and secure operation of each energy hub as well as plug-and-play functions.

It also converts the voltage and frequency levels and adjusts the power quality in real time.

3) Rapid fault detection and isolation is a unique feature of ER. It can detect faults and isolate the main power grid using fault detection module.

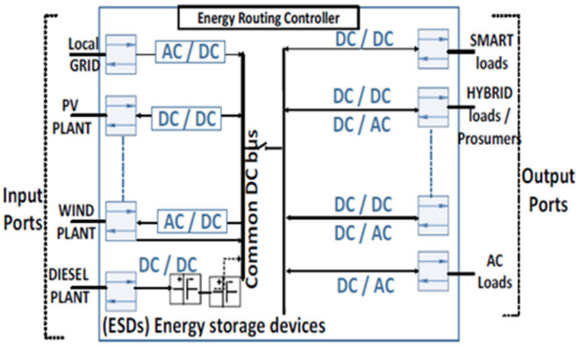

FIGURE 4. Basic layout of energy router [39].

C. IEC 61850 BASED ENERGY ROUTER

The aim of IoE is to build a feasible and flexible grid network/system. The ERs can efficiently handle this complicated power system network by reducing the line losses [64]. It can also integrate energy storage devices and DGs effectively without any issue. IEC 61850 is a communication standard or protocol that can bring diverse elements of a power network under a common roof because of its interoperable feature.

The interoperability of IEC 61850 standard can play vital role in solving the real-time implementation problem of ERs [53]. To achieve this goal, the researchers have modeled the ER as a logical device (LD) based on some logical nodes (LNs) defined in IEC 61850 along with some newly developed LNs.

In another research, IEC 61850 based plug-and-play interface has been described, which is a key technology of ER [69]. Here, the LDs have been divided into five parts; LD1 provides information to control unit and generates control signals, LD2 monitors the power system, LD3 is dedicated as the ECP, LD4 provides protection, and LD5 is a DC/DC converter. The LNs are defined based on the functions of plug-and-play interface. Both of these research works show pathways to build efficient ERs in a goal to improve the performance of IoE. Table 1 presents some summarized earlier research works on ER while Fig. 5 shows an IEC 61850 model of the ER.

VII. KEY TECHNOLOGIES OF IoE: POWER GENERATION EQUIPMENT

The IoE power generation equipment is comprised into both renewable and non-renewable or traditional power generation sources [70]. Examples of renewable energy resources include PV, wind, hydroelectric, biomass etc. Hydro power plant and biomass plant have been in use for longer time. On the other hand, wind, solar, geothermal, tidal resources are interests of present research. Among them, wind and PV power are the two most popular power generation technologies. These two power generation technologies are discussed briefly in the following sections.

TABLE 1. Summarized research works on energy routers.

Focus of Work	Research Method	Reference
Energy Routing based on IEC 61850	Theoretical (Algorithm), Network Simulation, Experimental (InfoTech 61850 ICD editor tool).	[40]
Coordinated control and energy management strategies for seamless transition between grid-connected mode and islanded mode.	Simulation (MATLAB/SIMULINK) and Experimental	[50]
Control of the LAN-level energy router	Simulation (SIMULINK)	[46]
ER towards IoE	Theoretical	[48,53,54]
Plug and play interface based on IEC 61850	Theoretical	[56]

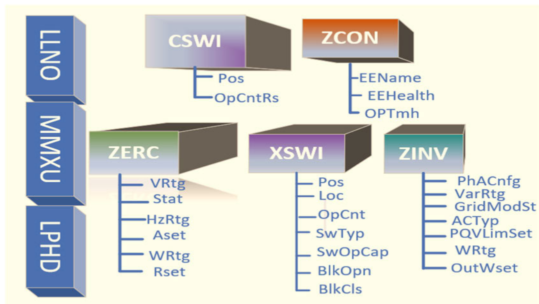

FIGURE 5. IEC 61850 model of energy router [39].

A. WIND POWER

In a wind power plant (WPP), the electrical power harnessed is dependent on wind speed [71]. In a high-speed wind area, wind cuts the blades of wind turbine which produces torque. This torque rotates an asynchronous generator rotor which is connected to high-speed shaft gearbox, and it keeps generating power. Wind energy is considered as one of the most efficient low-carbon technology options, which can reduce more than 25% of total pollution due to power generation by 2050 [72]. It is also considered as one of the large-scale development and promising power generation technology [73].

B. SOLAR POWER

Solar photovoltaic (PV) is the technology which converts sunlight into electricity using the photoelectric effect of

PV cell [54]. Similar to wind power technology, it is also a clean energy resource with a lot of other advantages such as, no fuel consumption, no geographical boundaries, time, and cost-efficient during installation, flexibility in design size, and so on. It has become one of the important factors for sustainable development of energy in a lot of countries. In the developed countries, solar power technology is used in most of the residential and commercial premises and more PV systems are being added to the grid as people are aware about clean energy technology. In the IoE framework, wind and solar can play significant role as it supports the concept of prosumers where the end-users can generate and sell electricity [74].

According to IEC 61850-7-420, communication in DER plant can be categorized into four parts such as, information modeling, services modeling, communication protocols, and telecommunication media [55].

It also noticed that according to the IEC 61850-7-420, IEDs could be configured for the DER plants. The DER plants are usually designed with three types of IEDs, namely, i) Protection and Control (P & C) IEDs, ii) Merging Unit (MU) IEDs, and iii) breaker IEDs [2], [55], [56]. Fig. 6 to Fig. 10 show the IED configuration of five different types of DERs. These are: a) PV plant, b) Wind farm, c) Diesel Generator, d) Battery Storages, and e) Controllable loads.

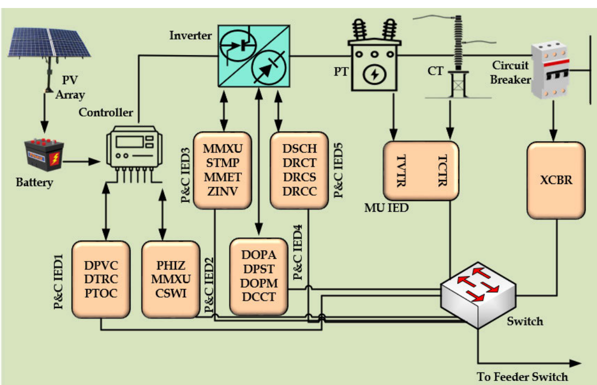

FIGURE 6. IED configuration for PV plant.

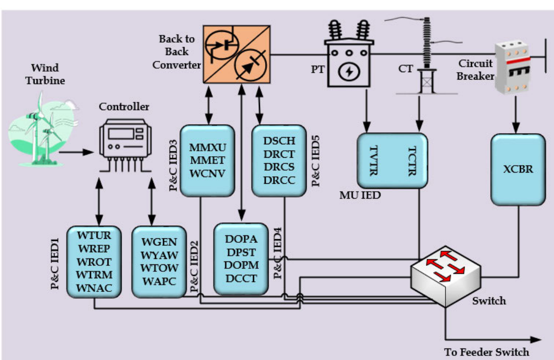

FIGURE 7. IED configuration for wind power plant.

Table 2 provides a short description of the logical nodes which are defined as of IEC 61850-7-2 and IEC 61850-7-420 except for the controllable loads. However, a new logical node named as CNLO has been developed through 'Generic Automatic Process Control (GAPC)' for controllable load as

TABLE 2. Logical nodes description [2], [27], [41], [51].

Protection	PTOC	Time over current
	PTUV	Time under voltage
	PIOC	Instantaneous over current
	PTOV	Time over voltage
	PHIZ	Thermal overload
Decentralized Energy Resources	DPVC	Photovoltaic array controller
	DTRC	Tracking Controller
	DOPA	DER operational authority at Electrical Connection Point (ECP)
	DPST	Provides status information at the ECP
	DOPM	Mode at ECP
	DCCT	Economic dispatch parameters
	DSCH	Provides DER energy schedule
	DRCT	DER controller characteristics
	DRCS	Control status of DER
	DRCC	Supervisory control of DER
	DRAT	Provides generator ratings
	DCST	Provides operating cost of generator
	DGEN	State of DER generator
	DCIP	Reciprocating engine control
	DEXC	Excitation settings
	DSFC	Information on speed or frequency controller
Transformer	TCTR	Current transformer
	TVTR	Voltage transformer
Switchgear	XCBR	Circuit Breakers
Control	CSWI	Switch Controller
	CLNO	Position and operation of Controllable load
Metering and Measurement	MMXU	Measurement
	MMET	Provides meteorological information
	MPRS	Pressure Measurement
Supervision	STMP	Temperature supervision and measurement
Wind Turbine	WTUR	General information
	WREP	Reports information on wind Turbine
	WROT	Rotor information
	WTRM	Transmission information
	WNAC	Nacelle information
	WGEN	Generator information
	WYAW	Yawing information
	WTOW	Tower information
	WAPC	Power plant active power control
	WMET	Meteorological information
	WCNV	Converter information
Power System Equipment	ZINV	Inverter
	ZBAT	Battery systems
	ZBTC	Battery Charger
	ZRTC	Rectifier

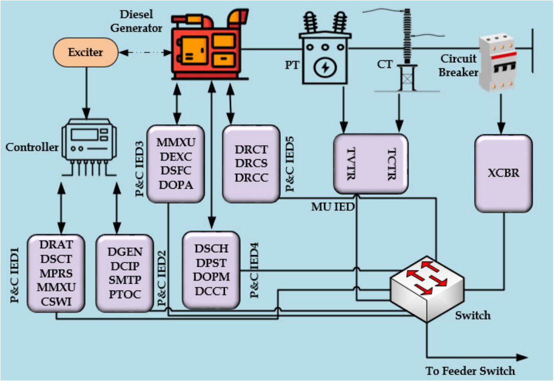

FIGURE 8. IED configuration for Diesel power plant.

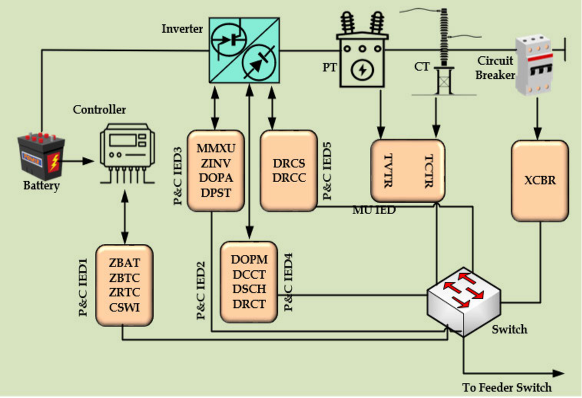

FIGURE 9. IED configuration for battery storage.

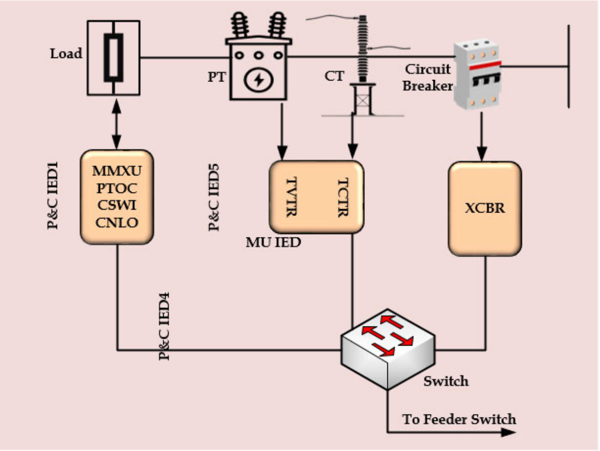

FIGURE 10. IED configuration for controllable load.

it has not been described by IEC 61850 standard [56]. All the DER plants have some logical nodes in common.

The breaker IED and MU IEDs have the same logical nodes, i.e., XCBR, TVTR, and TCTR. For P & C IEDs, some IEDs are common, such as CSWI, which is used for control of switching conditions. The IEDs in PV system has been designed for maximizing the power out of array and tracking, temperature measurements, DC to AC conversion, and observing the meteorological conditions.

In the wind firm or plant, the IEDs are modeled for back-to-back converter, for containing the information of wind turbine generator, nacelle, yaw and rotor respectively, active power control of wind power plant and wind power plant meteorological conditions. In the diesel plant, the DER control IED corresponds to the exciter and controller of the diesel plant, status information and controls of DER generator operations, excitation ratings, diesel engine characteristics, measured values and controls, and ratings and costs respectively associated with its operations [57]. The logical nodes of the battery storage mainly store battery data, battery information, including battery type, capacity, and charging [58]]. The controllable load model is mainly controlled by CNLO logical node which can update the position and operating mode of controllable load [2].

VIII. ENERGY STORAGE DEVICES

Energy storage devices build strong foundation for IoE as reported in [75]. The main objectives of energy storage devices are listed below.

1) Power quality and stability improvement is one of the main tasks of Energy storage devices. Distributed Energy Storage System (DESS) supports smooth power generation, reduces the impact of any sort of unbalances on power grid and consumers.

It also increases the time efficiency and reliability of the power grid. Combination of DER unit, power converters and energy storage devices reduce voltage drop, surge, and transient power outages, that means, the quality, reliability, and stability of power can be improved by integrating these three elements [76]. Hence, Energy storage devices can effectively improve the quality of dynamic power.

2) Energy storage devices can provide backup supply during grid failure or blackouts. Moreover, when the renewable energy resources go through some unpredictable weather conditions, for example, variation in wind speed and/or solar irradiance as well as in rainy days; then, the energy storage devices can play a vital role as an alternative and supply continuous power to the user/ consumers [77].

3) The prosumers in a smart grid network can contribute by selling surplus electricity that is stored in energy storage devices. Therefore, the storage devices could be a cost-effective tool for electricity market by meeting peak time power demand and emergency support services [78].

Till now, different types of energy storage systems (ESS) and corresponding devices have been invented. The major types of ESSs are classified as: i) mechanical, ii) electrical, iii) electrochemical, iv) thermal, and v) chemical storages [79]. The future research is also focusing on using the technologies like vehicle-to-grid (V2G) system using EVs [54].

Several research works have been conducted aiming at improving energy storage system for EV [80], [81], [82]; their contribution has been shown at Table 3.

A. IEC 61850 BASED ENERGY STORAGE DEVICES

1) BATTERY STORAGE SYSTEMS

In section V, the configuration of IEC 61850 based IEDs for battery storages have been discussed. Besides that, design of information model based on IEC 61850 has been shown in some other research works as reported in [58] and [83]. The information model, comprising generic data model and services, is flexible for modification due to Substation Configuration Language (SCL).

Fig. 11 demonstrates the classification of the information structure of the battery energy storage system into three layers: the device layer, the bay layer, and the management layer. At the core of the battery energy storage system lies the device layer, comprised of physical components such as the battery pack, DC breaker, DC current converter, measuring and monitoring equipment, AC breaker, and step-up transformer. The measuring and monitoring equipment, which includes devices like current transformers and potential transformers, plays a vital role in measuring and monitoring the operational data of the battery energy storage system, providing essential information for real-time analysis.

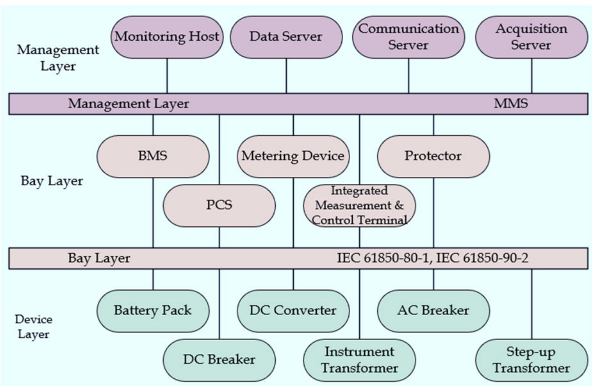

FIGURE 11. The arrangement of information pertaining to the battery energy storage system [87].

TABLE 3. Summarized research works on energy storage for EV.

Focus of Work	Research Type & Platform	Reference
Efficient sizing method and economic evaluations for II-Life ESSs supporting EV charging stations.	Simulation based on real case study	[84]
Hybrid Energy Storage Systems for Electric Vehicles	Analytical	[85]
Design of the Digital Low-Pass Filters for Energy Storage Systems in EV Applications	Theoretical, Simulation (MATLAB/SIMULINK), Experimental Theoretical	[86]

Finally, the AC breaker and step-up transformer facilitate the connection of the battery energy storage system to the external power grid.

Serving as the intermediary between the device layer and management layer, the bay layer enables the exchange of information. It receives measurement data and operational status information from the device layer, pre-processes the data, and transmits it to the management layer. Simultaneously, it receives, analyzes, and executes the control information from the management layer, facilitating device management. Key components of the bay layer include the battery management system (BMS), power conversion system (PCS), integrated measurement and control terminal, and protectors. These devices feature extended human-computer interaction interfaces, providing convenience for parameters configuration and operation debugging. The BMS is responsible for monitoring the battery, generating running alarms, conducting self-diagnosis, managing parameters, displaying running status, and enabling the storage and query of historical data. The PCS executes orders from either the management layer or the bay layer to connect the battery energy storage system to the grid or engage in islanding operation. The integrated measurement and control terminal is responsible for collecting data and transmitting control orders. Finally, the protectors provide fault protection and status alarms for the battery energy storage system.

The management layer comprises the monitoring host, operator station, and telemechanism communication device, offering a man-machine interface and managing and controlling the device layer and bay layer devices. Additionally, it formats the substation monitoring and management center and communicates with the remote monitoring and controlling center.

2) VEHICLE-TO-GRID (V2G) SYSTEM

Vehicle to Grid (V2G) technology could be simply defined as a system that facilitates the bi-directional flow of electrical energy between vehicles and the electrical grid. IoE can help this technology to exchange energy without developing separate transmission and distribution network. Information exchange is a vital aspect of V2G technology based on IoE. For communication protocol and architectures, network management, and network security issues, IoE uses ISO/IEC/IEEE 18880, ISO/IEC/IEEE 18881 and ISO/IEC/IEEE 18883 standards; whereas V2G uses IEC 15118 standard for communication between EV and EV charger [10].

IEC 61850 based V2G system is an emerging topic in the field of smart grid communication systems or networking. A V2G system has been proposed with Networked Electric Vehicle (NEV) and integration of IEC 61850 into the communication network is developed and shown in Fig. 12 [54].

This research explains how to integrate IEC 61850 into the V2G system, along with SCL file documentation, tabulated data set specification and IEC 61850 Gateway and Client deployment. In another research, the information model has

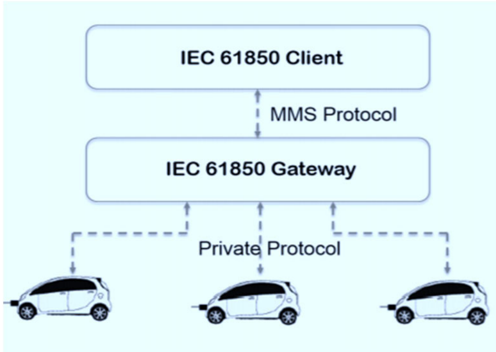

FIGURE 12. System architecture of the communication network in the V2G system with NEVs [37].

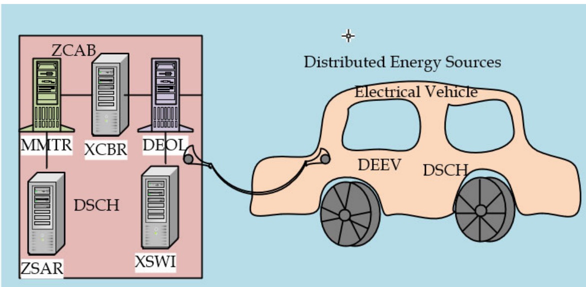

FIGURE 13. Illustration of the installation of logical nodes for charging infrastructure.

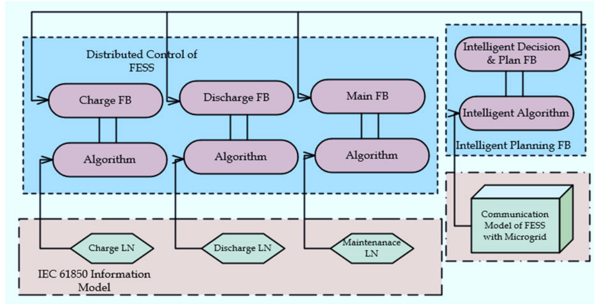

FIGURE 14. An all-inclusive design for FESS within a Microgrid [49].

been newly defined by extending the IEC 61850-7-420 to control charging and discharging of EVs [55], [87].

The logical node implementation of a charging infrastructure has been shown in Fig. 13. Here, DESE = E-mobility Supply Equipment; DEEV = Electric Vehicle; DEOL = Outlet; MMTR = Metering; XCBR = Circuit Breaker; XSWI = Circuit Switch; ZSAR = Surge Arrestor; DSCH = Schedule. Besides this, the total number of EVs that can communicate with the base station has been investigated and examined different scheduling algorithms to justify the scalability limit [88].

3) FLYWHEEL ENERGY STORAGE SYSTEMS (FESS)

FESS in distributed power automation environment of microgrid is focused as reported in [60]. Information and data modelling to adapt original mechatronic FESS to distributed power automation environment of Microgrid, distributed control mechanism for physical components of FESS, and intelligent decision and planning strategies for FESS charging and discharging procedure are considered.

A joint approach of IEC 61850 and IEC 61499 to facilitate FESS into microgrid has been considered in [60]. This research demonstrates a communication model between FESS and grid, which, as a result, aids intelligent decision and planning for charging and discharging procedure.

Fig. 14 illustrates an all-inclusive design for FESS within a microgrid. In this case, the IEC 61850 information model is divided into two parts. One part is designed to model communication data among components within the FESS, such as the rotating flywheel, motor working state transition between charging and discharging procedures, and magnetic floating bearing system. The primary function of this part is to specify the data flow among the distributed control structure within the physical components of FESS. The other part of the information model is intended for the interaction of FESS with microgrid facilities. Its function is to collect comprehensive information in the microgrid and provide the necessary support for implementing the intelligent mechanism of FESS.

The distributed control of physical components within the FESS is established using IEC 61499 [58]. Composite Function Blocks (FBs) are utilized to describe the control of flywheel rotation, motor state transition, and magnetic floating bearing system [58]. The data flow between these composite FBs facilitates the description of the distributed control execution mechanism within the FESS using Data Objects and Data Attributes as defined by IEC 61850. Events during these procedures, such as triggers for charging and discharging procedures, instantaneous data collection, state transition, and relevant algorithms of physical components, are defined. The FESS distributed control is independently defined with an intelligent decision mechanism in mind, which enables the FESS to fit into a distributed power automation environment and enhances its reconfigurability [58]. In the context of this diverse array of power generation sources, it becomes evident that integrating classical grid principles into discussions about the transformation to smart grids is essential for ensuring a seamless transition and optimizing the utilization of both traditional and renewable energy resources [21].

IX. CONCLUSION

In conclusion, the potential application of IEC 61850 for enabling IoE in smart grids has been explored. It has reviewed the existing research works on the key technologies of IoE, such as energy routers, power generation equipment, and energy storage devices, and how they can be integrated and controlled using IEC 61850. A summary of research works on the key technologies of IoE has been shown in Table 4. Moreover, it has also discussed the benefits and challenges of using IEC 61850 as a communication standard for IoE, such

TABLE 4. Summarized research works on key technologies of IoE.

Key technologies of IoE		Research Method	Reference
Energy Router (ER)		Theoretical (Algorithm), Network Simulation, Experimental (InfoTech 61850 ICD editor tool).	[49]
Power Generation Equipment	PV	Simulation (OPNET, Modbus unit, Ellipse Software)	[2][89]
	Wind	Simulation (OPNET), Theoretical	[2] [90]
Energy Storage Systems (ESS)	Battery	Simulation (OPNET), Theoretical	[2] [58] [80]
	V2G	Mathematical Modelling, Simulation	[51][52] [87]
	FESS	Theoretical	[54]

as interoperability, scalability, security, and performance. The paper has shown that IEC 61850 can provide a robust and flexible platform for information exchange and management among various smart grid entities and applications. The future electricity grid will highly rely on IoE based on IEC 61850 to ensure smooth communication between the grid and the prosumers. This is because IEC 61850-7-420 has already defined logical nodes for DER, EV and energy routers. Therefore, integration of IEC 61850 with IoE can be helpful for future research works related to IoE and its development towards achieving smart grid goal. Hence, this paper has suggested some future research directions for improving the IEC 61850 based IoE system, such as developing new logical nodes, enhancing the middleware technology, and incorporating blockchain and artificial intelligence. Finally, it can be concluded that the combination of IEC 61850 and IoE can contribute to the development of a more efficient, reliable, and sustainable smart grid network system.

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NAROTTAM DAS (Senior Member, IEEE) received the B.Sc. degree (Hons.) in electrical and electronic engineering from Chittagong University of Engineering and Technology, Chittagong, Bangladesh, the M.Sc. degree in electrical and electronic engineering from Bangladesh University of Engineering and Technology, Dhaka, Bangladesh, and the Ph.D. degree in electrical engineering from Yamagata University, Japan. His Ph.D. research Project was funded by the Ministry of Education, Sports and Culture, Government of Japan. He has about three decades experience as an academia and industrial Engineer in Australia and overseas. Currently, he is a Senior Lecturer in electrical engineering with the School of Engineering and Technology, Central Queensland University Australia, Melbourne Campus, VIC, Australia. He is the author/coauthor of over 220 peer-reviewed journals and international conference proceedings, including eight book chapters and four edited books; nano-structured solar cells, advances in optical communication, optical communication, and optical communication systems. His research interests include in power systems communication (smartgrids) using IEC 61850, multi-junction Solar (PV) cells, modeling of high efficiency solar cells (renewable energy), and high-speed communication devices. He is also a Guest Editor of the *Energies* (MDPI) Special Issue on "Nano-Structured Solar Cells," an Editorial Board Member of *Energies*, and a Topic Editor of Special Issue on "Solar Energy and Photovoltaic Systems." He is also an Executive Committee Member of Electrical College Victoria Branch (ECVB), Engineers Australia, a Secretary of the IEEE PES, PHS and IEEE IAS, and Victorian Section, USA. He is a Senior Member of the IEEE PES and PHS, USA; a fellow of the Institution of Engineers, Australia; a C.P.Eng., NER; and a Life Fellow of the Institution of Engineers, Bangladesh.

AKRAMUL HAQUE received the B.Sc. degree (Hons.) in electrical and electronic engineering and the Master of Science (M.Sc.) (Engineering) degree from Chittagong University of Engineering and Technology (CUET), Bangladesh, in 2013 and 2021, respectively. He is currently pursuing the Doctor of Philosophy degree with the Faculty of Engineering and Information Sciences, School of Electrical, Computer, and Telecommunications Engineering, University of Wollongong, NSW, Australia. Since 2020, he has been an Assistant Professor in electrical and electronic engineering with Premier University, Chittagong, Bangladesh, where he was a Lecturer, from 2015 to 2019. Earlier, he has also operated as a Quality Assurance Engineer in a transformer manufacturing company named Integral Electric Company, Chittagong. His research interests include distributed energy resources (photovoltaic, wind energy, and battery storages) integration to the microgrid, electric vehicle coordination, energy management, power systems stability, and control.

HASNEEN ZAMAN received the B.Sc. degree (Hons.) in electrical and electronic engineering from Chittagong University of Engineering and Technology, Chittagong, Bangladesh, in 2013. She also received the Graduate Certificate in Research (GCR) with major in electrical engineering from Central Queensland University Australia, in 2021. Currently, she is an Electrical Engineer with Coengineer, NSW, Australia. Earlier, she was a Research Assistant with CQUniversity Australia. Before moving to Australia, she was a Lecturer in electrical and electronic engineering with East Delta University, Chittagong. She was an Assistant Electrical Engineer with Surprise Industrial Corporation, Chittagong. She has completed her industrial training (Internship) with the Training Institute for Chemical Industries (TICI), Narsingdi, Dhaka, Bangladesh. She is a member of the Institute of Engineers Bangladesh (IEB). Her research interests include smart grid communications for modern power system networks and digital signal processing.

SAYIDUL MORSALIN (Member, IEEE) received the B.Sc. degree (Hons.) in electrical and electronic engineering from Chittagong University of Engineering and Technology, Bangladesh, in 2013, the M.Res. degree (Hons.) from Macquarie University, Australia, in 2016, and the Doctor of Philosophy (Ph.D.) degree from the Energy Systems Research Group, The University of New South Wales (UNSW), Sydney, NSW, Australia, in 2020. Currently, he is a Senior Engineer with AGL, Sydney. His research interests include smart grids, diagnostic testing in high-voltage engineering, and power systems. He received the Dean's Award for the Ph.D. degree.

SYED ISLAM (Life Fellow, IEEE) received the B.Sc., M.Sc., and Ph.D. degrees in electrical power engineering, in 1979, 1983, and 1988, respectively. Currently, he is the Executive Dean and Professor with the School of Science, Engineering and Information Technology, Federation University Australia, Ballarat, Melbourne, VIC, Australia. He received the IEEE T Burke Haye's Faculty Recognition Award, in 2000. He has published over 300 technical articles in his area of expertise. His research interests include condition monitoring of transformers, wind energy conversion, and power systems. He has been a keynote speaker and an invited speaker at many international workshops and conferences. He is the current Chair of Australasian Committee for Power Engineering (ACPE) and a member of the Steering Committee of Australian Power Institute. He is a fellow of the Engineers Australia, IEEE IAS, PES and DEIS, IET, and a Chartered Engineer in the United Kingdom. He is a Regular Reviewer of IEEE Transactions on Energy Conversion, IEEE Transactions on Power Systems, and IEEE Transactions on Power Delivery. He is an Editor of IEEE Transactions on Sustainable Energy. He is also an IEEE PES Distinguished Lecturer.