Received June 28, 2019, accepted July 15, 2019, date of publication July 17, 2019, date of current version August 6, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2929577

Multi-Agent Systems in ICT Enabled Smart Grid : A Status Update on Technology Framework and Applications

MOHAMMAD HASANUZZAMAN SHAWON[1], (Student Member, IEEE), S. M. MUYEEN[1], (Senior Member, IEEE), ARINDAM GHOSH[1], (Fellow, IEEE), SYED MOFIZUL ISLAM[2], (Fellow, IEEE), AND MURILO S. BAPTISTA[3], (Senior Member, IEEE)

[1]School of Electrical Engineering, Computing and Mathematical Sciences, Curtin University, Perth, WA 6102, Australia
[2]School of Science, Engineering and Information Technology, Federation University Australia, Melbourne, VIC 3350, Australia
[3]Department of Physics (ICSMB), University of Aberdeen, SUPA, Aberdeen AB24 3FX, U.K.

Corresponding author: Mohammad Hasanuzzaman Shawon (mhshawon@student.curtin.edu.au)

ABSTRACT Multi-agent-based smart grid applications have gained much attention in recent times. At the same time, information and communication technology (ICT) has become a crucial part of the smart grid infrastructure. The key intention of this work is to present a comprehensive review of the literature and technological frameworks for the application of multi-agent system (MAS) and ICT infrastructure usages in smart grid implementations. In the smart grid, agents are defined as intelligent entities with the ability to take decisions and acting flexibly and autonomously according to their built-in intelligence utilizing previous experiences. Whereas, ICT enables conventional grid turned into the smart grid through data and information exchange. This paper summarizes the multi-agent concept of smart grid highlighting their applications through a detailed and extensive literature survey on the related topics. In addition to the above, a particular focus has been put on the ICT standards, including IEC 61850 incorporating ICT with MAS. Finally, a laboratory framework concepts have been added highlighting the implementation of IEC 61850.

INDEX TERMS Multi-agent, IEC 61850, smart grid, ICT.

I. INTRODUCTION

The word ''Smart grid'' has become a buzzword all over the world. A smart grid is defined by a bidirectional flow of electric power and data/information in order to establish a decentralized and intelligent electric power network among numerous interconnected elements (Generation-Transmission-Distribution) [1]. It is broadly accepted that ICT platform is playing one of the most vital roles in the establishment of smart grid concept. Due to the complex, distributive and highly unpredictable nature of smart grid, the control system has been evolving from centralized imposing architecture towards the decentralized, autonomous, flexible and robust structure. Multi-agent system (MAS) has emerged as an essential and useful tool to solve the implementation challenges of smart grid.

A multi-agent system is defined as a coalition of a number of intelligent agents cooperating in order to achieve a specific objective, thus accomplishing the overall goal of the system. In contrast with Supervisory Control and Data Acquisition (SCADA), in a traditional power system, MAS based applications have introduced a new paradigm in developing decentralized systems including many features such as autonomy, sociality, reactivity, and pro-activity. In parallel with that, artificial intelligence has enabled MAS approaches to replace human operator in the power system especially in case of automated operation. In the literature, a wide range of works have been published on the topic of MAS which can be categorized into two-fold aspects from a broader point of view. The first one is the MAS concept, approach, design and challenges in its implementation [2]–[4]. The second one is the MAS based application in numerous technological categories such as grid control [5], protection [6], electricity market simulation [7], power system model [8], network operation [9], substation automation [10] and others. In addition to that, a number of review papers and surveys papers exist in the literature which summarizes MAS based application in the field of power

The associate editor coordinating the review of this manuscript and approving it for publication was Francesco Piccialli.

engineering [11]–[14], MAS toolkits/software[15]–[17], MAS real-time applications [18], [19] and some other bibliographical analysis. However, little emphasis has been given on the ICT structure of the smart grid enabling an underlying MAS based operation. Simulations of potential case studies are also absent. It is then clear that MAS is becoming the norm in new developments for the smart grid. Since ICT is fundamental to its implementation, a new scope of MAS and ICT application in the smart grid is urgently needed. This work addresses the challenges for the integration of MAS and the ICT platform in the smart grid, additionally highlighting a protection mechanism following an IEC standard.

So, the primary goal of this work is to introduce a brief overview of the modern decentralized smart grid employing multiple intelligent agents, its applications in different segments and the implementation of one of the communication standards-IEC 61850. The concept, architecture, benefits, and applications in the use of intelligent agents in the smart grid have been summarized following an extensive literature review. In addition to that, a detailed literature review of IEC 61850 has been performed in the context of substation automation, protection, control, and security. This work aims at the application of a MAS architecture enabled by a communication platform for the smart grid. This review is organized into seven sections. Section 2 presents the introduction of the modern decentralized smart grid and the concept behind it, Section 3 highlights the literature statistics of MAS research while the definition of agent concept, benefit, architecture, platforms is presented in section 4. Section 5 focuses on the introduction of communication platforms for the smart grid with a particular highlight on IEC 61850. The task of IEC 61850 for substation (Intelligent Electronic Devices) IED automation, control, and protection is briefly summarized with a detailed literature survey in this section. The applications of a multi-agent system (MAS) with an enabling ICT structure in the smart grid is presented in section 6 categorizing into different sections, and each section consists of a detailed literature survey of MAS. Finally, section 7 comprises a laboratory test framework employing the IEC 61850 standard for a smart grid protection system at Curtin University. Section 8 concludes the paper.

II. OVERVIEW OF ICT ENABLED SMART GRID

The Smart Grid idea has called for a revolutionary change in the concept of the conventional electric grid. The traditional way in which generation, transmission, distribution, control, and protection happens in the conventional electrical power grid is being completely transformed. The modern Smart Grid is idealized as an automated, resilient, intelligent structure. In other words, a Smart Grid is an intelligent electrical network combining all the parties involved in the grid – generators, consumers and prosumers to secure sustainable, efficient, reliable and economic electric power supply employing modern digital technologies, self-regulating monitor and control strategies and advanced information and communications technology (ICT). In the pathway to create the Smart Grid, modern and new edge technologies, innovative products and services facilitate the environmentally friendly distributed generation, the reliable and efficient transmission and distribution of energy, the resource-cheap and real-time monitoring, with unsupervised control, and unlimited protection of the grid, the efficient communication, the optimal demand response, the necessary energy storage facilities, and self-healing technologies. The whole power grid network and participating parties including distributed energy resources (DERs), distribution system operators (DSOs), transmission system operators (TSOs), consumers/prosumers and market mechanisms are continuously evolving around the smart grid to maintain its ‘smart’’ status quo. In this regard, digital information and communication technology (ICT) plays a very vital and core part in the evolution of this smart grid which has been depicted in Fig. 1. In the generation part of the smart grid, Distributed Energy Resources (DERs) brings the solution of environment-friendly and sustainable energy production in parallel with the conventional energy plants [20], [21]. In the transmission level, Synchrophasor based WAMS (Wide area monitoring system) technology has emerged as a game changer and transforms the grid into a smart one [22]. WAMS facilities real-time monitoring of complex power grid across larger areas employing PMUs (Phasor measurement units) and thus outshines the traditional Supervisory Control and data acquisition (SCADA) systems [23], [24]. The smart distribution system includes functionalities like self-healing of grid [25], smart energy management [26], intelligent monitor and control based on smart automation devices or intelligent nodes [27], integration with EVs (Electric Vehicles) [28], facilitating energy storage technology [29] and so on. The role of consumers in the smart grid has changed drastically and with the increased penetration of DERs, nowadays consumers are defined as prosumers and are contributing towards bidirectional power flow in the smart grid [30].

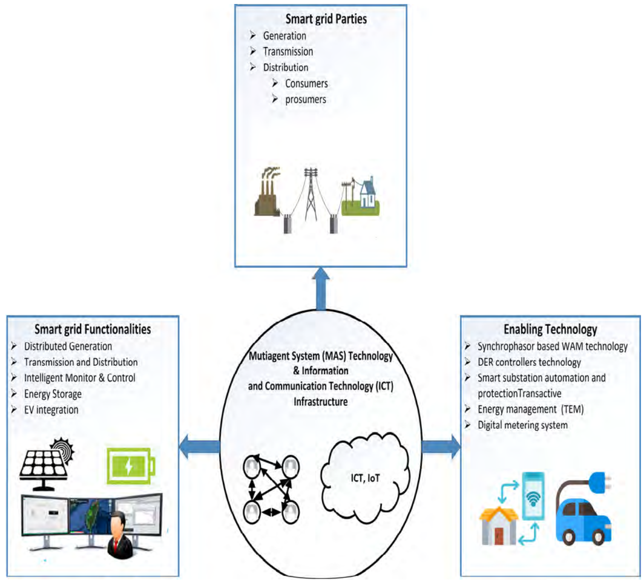

FIGURE 1. Bridging among different parties, functionalities in smart grid.

TABLE 1. Summary of ICT standards and application in smart grid.

Medium	Technology	Standard	Application
Wired	PLC	IEEE P1901.2, IEEE 1901	HAN, NAN, WAN
	Optical Fiber	PON,WDN,SONET/SDH	WAN
	DSL	ADSL, VDSL	NAN
	Ethernet	IEEE 802.3, IEC 61850	HAN, SAS
Wireless	WPAN	Bluetooth, ZigBee	V2G, HAN
	WLAN	IEEE 802.11z	HAN,NAN,V2G
	WiMAX	IEEE 802.16	NAN, WAN
	Cellular	2G,2.5G,3G,4G	V2G,NAN,WAN, Smart Meter

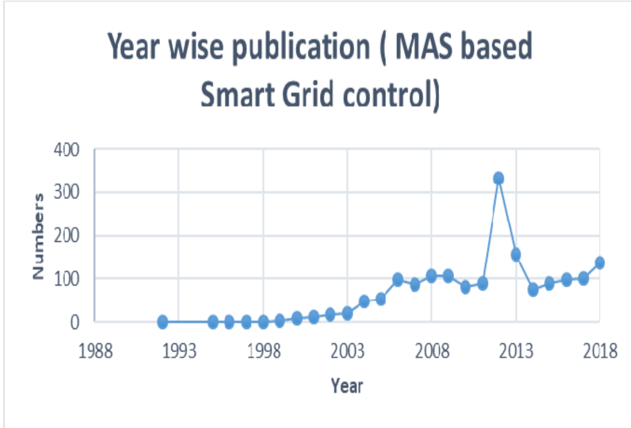

FIGURE 2. Year-wise publication on MAS technology available in the literature.

Additionally, consumers and prosumers have started to participate in demand-side energy management (DSEM) through the smart metering system and smart grid ICT market mechanism [31]. Different communication technologies have been employed via two major media: wired and wireless. Wired communication medium includes Ethernet, power line communication-PLC, optical fiber and wireless communication comprises satellite, WiMAX, cellular, z-wave [32]. A number of standards have been proposed in the evolution process of smart grid architecture such as IEC 61970/61968-CIM, IEC 61850, IEC 62351, IEC 62325 and so on [33]. A comprehensive summary of the available communication technologies for smart grid is presented in the Table 1 [34], [35].

III. MULTI-AGENT SYSTEM (MAS) TECHNOLOGY: LITERATURE STATISTICS

The Multi-agent system (MAS) technology enables the transformation of the centralized grid into the decentralized smart grid. It provides flexible distributed control for the grid and thus fulfils some essential criteria for the smart grid such as automatic fault identification, isolation, and restoration (FLISR) [36]. Extensive research works have been found in the field of MAS and Smart Grid. Fig. 2 presents year wise publication in the field of MAS technology-based smart grid (1992-2018) using a comprehensive SCOPUS database tool.

IV. AGENT DEFINITION AND CHARACTERISTICS

The objective of the multi-agent system is to segment a centralized system into several entities, commonly known as a decentralized system in order to solve a complex problem Intelligent agents must have the characteristics of autonomy, reactivity, pro-activeness and sociability [37]. Usually, an intelligent agent consists of four components input interface, output interface, decision mechanism and communication stricture [38].

A. THE ARCHITECTURE OF MAS IN SMART GRID

MAS can consist of a large number of agents participating in the complex phenomena of a smart grid. In order to avoid possible conflict of interest, the role of agents should be elaborated and defined in a decentralized power system. In this section, a detailed literature survey has been performed to identify different structures of MAS discussed in the smart grid. The first architecture is the centralized concept where the agents are working under a central agent [39, 40]. The subordinating agents are called a reactive agent (low-level intelligence and limited communication) and a master agent is termed as cognitive agent (high-level intelligence and higher communication). A cognitive agent has the responsibility of taking the central decision, communicating reactive agents and managing the network whereas reactive agent only accesses the local data and performs actions requiring a faster response (tripping a circuit autonomously). Such concept of a centralized architecture of MAS has also been mention in [41]. On the other hand, distributed architecture can be formed as a number of agents communicating through a common interface. Agents have the individual knowledge of their parts and have the capabilities of performing the local tasks instead of having global knowledge. The communication among the agent is performed through a common interface-agent directory. Agents can see the activities of the other agents via this agent directory which is described as a yellow page.

Example of such distributed architecture of MAS has been discussed in [42]. Fig. 3 presents a centralized MAS structure in smart grid where the agents (agent 1, agent 2... agent 4) work as reactive agents, they are supervised by a cognitive agent and all critical decisions are taken by this supervisory agent.

Another approach in MAS structure in microgrid/smart grid is the hierarchical approach [43]. The majority of MAS based implementations in smart grid/microgrid found in literature have followed two level or three-level hierarchal architecture [44], [45]. In [46], a three-level hierarchy has been illustrated where the upper-level agents are related to grid operators or distribution system operators who take part in decision making, solving global problems, coordinating with mid or lower level agents, processing of data

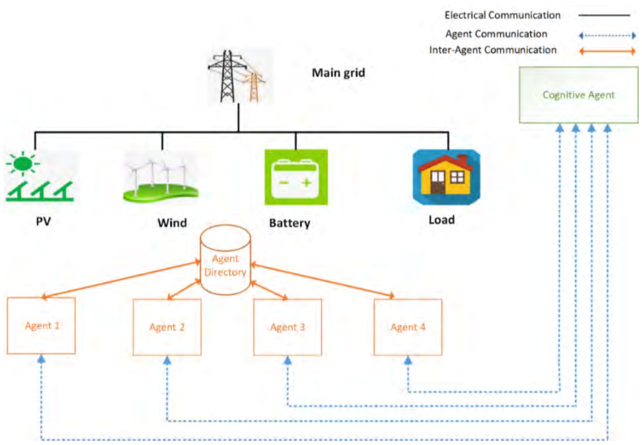

FIGURE 3. Centralized (supervising cognitive agent) and Distributed (reactive agents communicating over the agent directory) concept of MAS based smart grid.

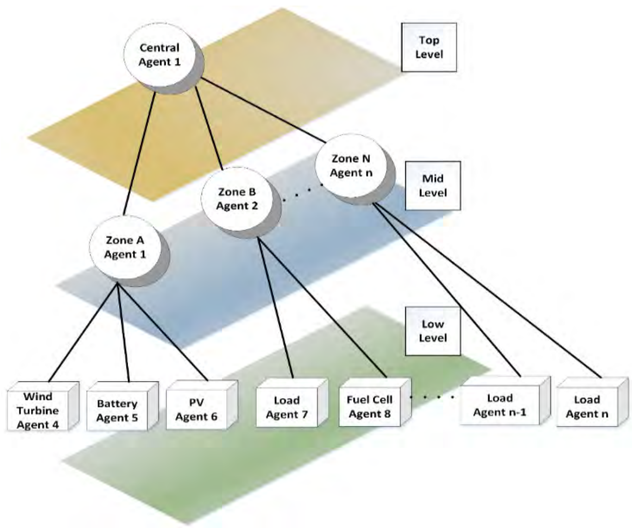

FIGURE 4. A 3-level hierarchal architecture of MAS based smart grid.

and handling ICT protocols. Mid-level agents perform grid operation such as islanding operation or grid connection operation, communicate low-level agents for a specific task such as FLSR service. The bottom level agents are equipped with sensors and controllers (e.g., Breakers, DERS, Batteries and loads). In Fig. 4, a 3-level hierarchical MAS architecture is illustrated where the low level is comprised of load agent, generation agents 4, 6 and 8 (wind turbine, PV fuel cell) and energy storage agent 5 (Battery) located in two separate zones of a distribution network. One zone comprises agents 4, 5 and 6, another zone comprises agents 7 and 8. These two zones are monitored by two zone monitoring agents residing in the mid-level. In the top level, a grid supervisory agent acts as DSO taking all the central decision.

In [47] conventional agents such as DER agents, Load agent have been modelled whereas some works have presented service based agent such as electricity market planning agent, grid planning agent [48], [49].

V. MAS & ICT BASED SMART GRID: METHODOLOGY, STANDARDS AND DEVELOPMENT PLATFORMS

This section summarizes the methodology, standards and development Platform of MAS based smart grid in the literature. Fig. 5 describes a generalized framework for MAS integrated smart grid system consisting of three stages: methodology, available standards, and development platform respectively. The generalized methodology (Requirement analyse-Design-Implementation-Deployment) to create a MAS based system has been discussed in [50]. Additionally, other methodologies have been discussed in literature for MAS design, such as GAIA [51], SODA [52] and others.

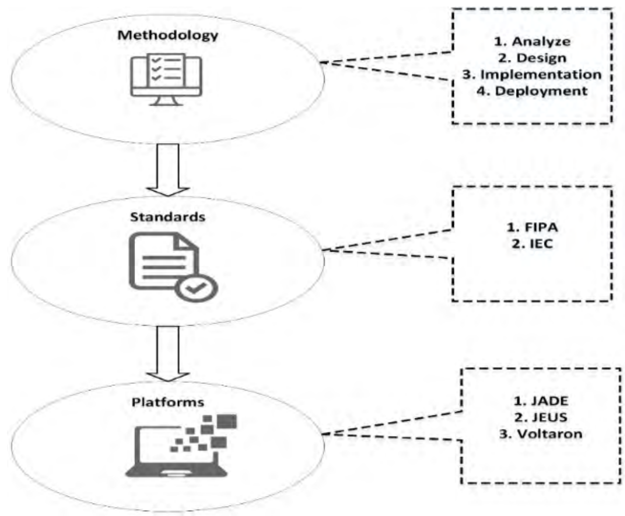

FIGURE 5. MAS based smart grid development stages.

With the development of ICT and smart grid, there was a need for data interoperability among different devices as well as integrating with existing systems. Hence, several standards and specifications have been proposed by IEEE working groups and IEC such as Foundation for Intelligent Physical Agents (FIPA) [53] and IEC 61850 [54].

FIPA facilitates all the agents to communicate among themselves and thus ensuring data interoperability. It also provides two directories namely "agent management service (AMS)" containing registered agents' list and "directory facilitator (DF)" containing services provided by the registered agents [3]. FIPA employs KQML (Knowledge Query and Manipulation Language) [55] and ACL (Agent Communication Language) for standard communication language [56]. Ontologies also have an important part in the messaging structure defining concepts and relations among the agents [57]. The components according to FIPA standards are presented in Fig. 6 where two agents are communicating among themselves using ACL.

Numerous number of software and toolkits have been developed in order to implement MAS platform[50]. They range from their compatibility, operating system, application fields and distinctive features as well as help support from the developers. A comparison between different MAS development platforms is presented in Table 2 in order to have a

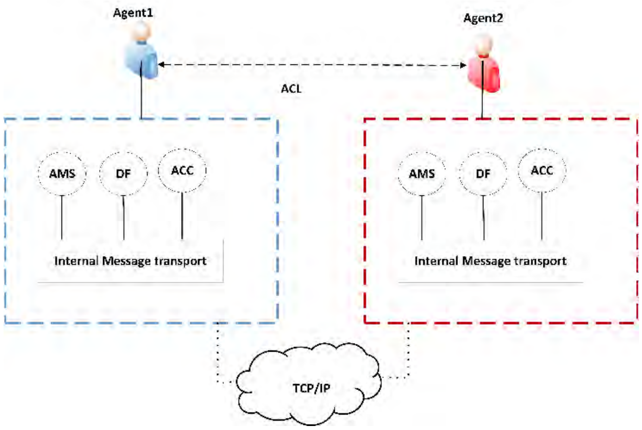

FIGURE 6. FIPA Agent platform architecture.

TABLE 2. Comparison of MAS development platform.

Platform	FIPA supported	Open Source	Editor	Programming Language	Features
JADE	✓	✓	Command Line	JAVA	Widely used, good documentation, microgrid scaling
JANUS	✗	✓	XML mining	Ordinary programming	Discontinued platform, weak documentation
JEUS	✓	✓	GUI	JAVA	Discontinued platform, weak documentation
Voltaron	✓	✓	Command Line	Independent of Programming	Hardware driver support, limited industry application

view on the development platform employed in smart grid available in the literature.

Having a highly cross-functional architecture, the smart grid has become immensely complex and rapidly developing concept integrating electric power layer and communication technology layer simultaneously. This information and communication technology platform consists of a number of communication structure to incorporate the electric power generation, transmission, and distribution and consumers/prosumers. IEEE 2030-2011 is one of the most widely adopted standards that provides smart grid's communication architectural overview [58]. Smart grid communications architecture has been categorized into three subgroups by IEEE 2030 standard – Home area network, Neighborhood area network and Wide area network [59]. A graphical representation of these subgroups including layers of the smart grid is shown in Fig. 7. Typically, Wide Area Network (distance > 10 km) covers generation and transmission part (power stations, PMUs, protection and control units, several NANs) while Neighborhood Area Network (distance 100 m-10 km) covers distribution side (DERs, protection and control unit, multiple HANs) and Home Area Network (distance < 100 mm) covers the consumers side (Smart meters, EVs, sensors). All the communication technologies are facilitated by both wired and wireless media with a data speed ranging from Kbps to Gbps and following a number of standards proposed by IEEE and IEC. However, this paper only focuses on extensive review on the standard IEC 61850-substation automation Systems.

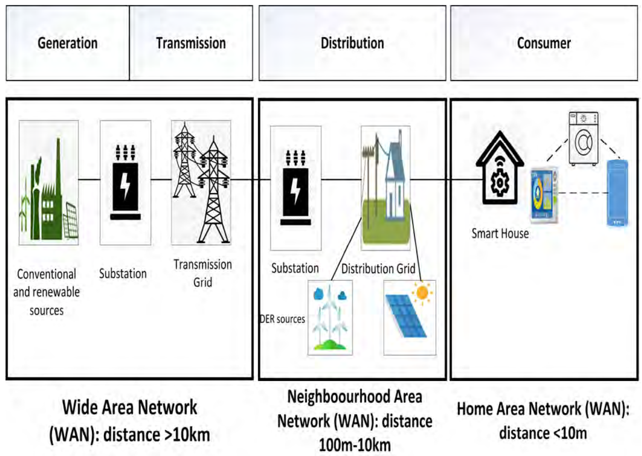

FIGURE 7. Smart grid communications architecture.

A. IEC 61850: A QUICK LOOK

IEC 61850 is an Ethernet-based communication standard proposed by the International Electrotechnical Commission (IEC) aiming for the substation automation and protection [60]. Replacing DNP3 (Distributed Network Protocol, version 3) [61], IEC 61850 intends to cover all aspects of substation automation technology by reducing the complexity and maintenance cost, specifying protocols such as TCP/IP, UDP/IP and ensuring data interoperability among multivendor IEDs (Intelligent Electronic devices) [62]. The timing requirements for information and data exchange in power substations is thoroughly described by IEC 61850 varying from (ranges from 3 ms to 500 ms) [63].

Fig. 8 presents a detailed architecture of IEC 61850 along with communication strategy. The IEC 61850 communication architecture consists of three levels: station, bay and process level respectively. Measurement devices such as CT/PT, I/O devices, sensors, and actuators correspond to process level whereas Bay level have IEDs and the station level comprises Human Machine Interface (HMI) and station controllers. Several works have been found in the literature regarding the architecture of IEC 61850 [64], [65]. Multi-agent based smart grid automation architecture employing IEC 61850/61499 intelligent, logical nodes have been focused in [66]. Reliability and availability

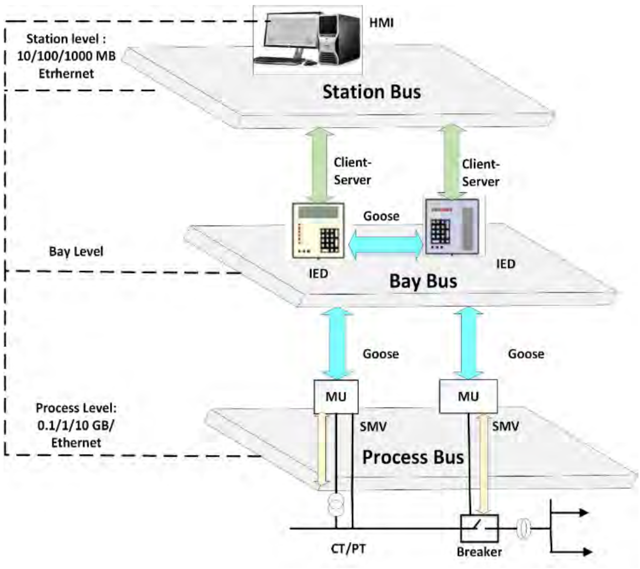

FIGURE 8. Architecture of an IEC 61850 for substation automation system.

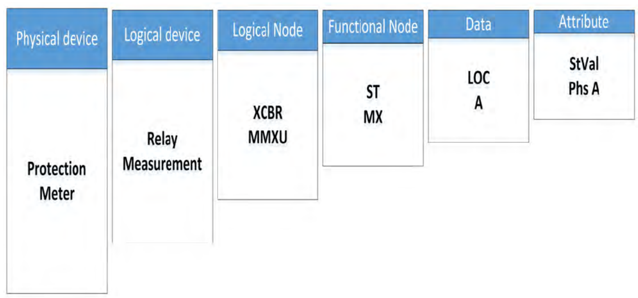

FIGURE 9. Node structures of IEC 61850 for protection and measuring unit.

analysis of IEC 61850 communication architectures have been performed in [67], [68].

Being an object-oriented protocol IEC 61850 breaks down a physical device into logical devices, which can be further broken down into Logical Nodes, Data Objects and Data Attributes [26] depicted in Fig 9.

IEC 61850 allows mapping of abstract data model and service definition into a number of protocols. In [69], the mapping of IEC is mainly divided into two segments, client-server based communication (SCADA) and publisher, subscriber-based communication respectively. In the [70], authors presents five types of communication services in IEC 61850 such as Abstract Communication Service Interface (ACSI), Generic Object Oriented Substation Event (GOOSE), Generic Substation Status Event (GSSE), Sampled Measured Value (SMV), MMS (Manufacturing Message Specification) and Time Synchronization (TS) based on various applications of these protocols and according to their traffic flows. The ACSI service presents a group of services and the responses corresponding to those services and hereby enabling symmetrical behavior of all the IEDS of a particular network.

TABLE 3. IEC 61850 communication protocols.

Communication Architecture	Service	Message Type	Application Type	Time Requirement (ms)	Communication Mapping
Client-Server (SCADA)	ACS	2	Moderate speed	100	Ethernet TCP/IP
		5	File Transfer	>= 1000	
Publisher-subscriber	GOOSE, GSSE	1A	Trip	3-100	Ethernet
		1B	Others	20-100	
	SMV	4	Measurement data	3-10	Ethernet
	TS	6	Synchronization	N/A	Ethernet UDP/IP

In other words, the data and the service model of ACSI are mapped to MMS (Manufacturing message specification) [71]. GOOSE and GSSE protocols, generally known as Generic Substation Events (GSEs), are employed to exchange critical data such as control signal and status information for example warning event in real time. The

GOOSE protocol presents a fast horizontal communication service among different IEDs including interlocking and blocking and thus facilitates publisher-subscriber mechanism [72]. Analog data such as current and voltage measurement are exchanged through Sample Measured Value (SMV) protocol. Both GOOSE and SMV are directly stacked on Ethernet. The system clock is usually broadcast by the TS service to synchronize with the IEDs for the accuracy of measurement. The GPS and the IEEE 1588 Precision Time Protocol (PTP) are the most widely used tool for this purpose [73], [74]. The summary of IEC 61850 based communication protocol, message time, time requirement and application is presented in Table 3 [75]–[77]:

VI. MAS APPLICATION IN SMART GRID

This section reviews the application of MAS in the smart grid that have been discussed in the literature. It has been divided into sections spanning several categories based on the particular application: smart control, operation and management; smart grid protection; monitor; smart grid transactive energy management; smart grid security.

A. SMART GRID CONTROL, OPERATION AND MANAGEMENT

A number of works have been found and that utilizes the MAS strategy to control the grid Smart grid Control, Operation, and Management. They have been summarized in Table 4.

B. SMART GRID PROTECTION

Several approaches that utilizes the MAS strategy for the protection of the smart grid including different communication platform have been recently proposed, this subsection summarizes some of them. In [93] the authors focus on

TABLE 4. Literature review summary: Smart grid control, operation, and management.

Literature Review	Type of control	Research focus/Technical Implementation	ICT platform
[78-80]	Load frequency control	ZEUS platform based IDPAS, MAS reinforcement learning (MARL) approach	FIPA
[81-85]	Voltage and Reactive Power Control	MAS-based voltage control for DC distribution, JADE platform based 2 way communication, smart inverters and Data Distribution Service (DDS), DER Ancillary Service in a cyber-physical test bed, Hierarchical Microgrid Control	IoT, IEC 61850, FIPA, IEC 61850, DDS
[86, 87]	Microgrid Islanding	ADIPS / DASH-based multi-agent framework, RTDS based implementation for IEEE 9bus system, decentralized hierarchical microgrid operation scheme	IEC 61850
[88, 89]	Network optimization	Real-time and adaptive Volt/VAr optimization (VVO)/conservation voltage reduction (CVR) system, real-time co-simulation platform for volt-VAR optimization (VVO) of smart grid	IEC 61850, IEC 61850-DNP3
[90, 91]	Self-healing and control strategy	FLSR testing in a physical dc grid model employing several Arduino microcontrollers and Raspberry Pi computers, simulation of autonomous self-healing network	IEC 61850
[92]	AuRA-NMS	MAS technology-based software architecture and the hardware platform	FIPA

the implementation of MAS based auto-configurable protection scheme using an agent-based architecture with the IEC 61850/IEC 61499. Another MAS based autonomous microgrid protection employing DERs, IEDs and IEC 61850 is described in [94]. A simulation-based study was performed in [95] for an IEEE 39 bus test system for MAS based protection scheme using FIPA compliant JADE platform. Self-Healing strategy with MAS based system and system restoration (Resilient Microgrid) is focused in [96]–[101]. The mapping between a multi-agent based architecture for power system control and the IEC 61850 standard for utility automation is highlighted in [102], which depicts how a relay agent in a particular substation is mapped into different levels according to IEC 61850 including different LN interaction. Additionally, this relay agent at a particular substation can communicate with another relay agent located at another substation using ACL. In the control mechanism, the relay agent continuously monitors the network and gets triggered upon observing a current value higher than the threshold value, and breaker operates and thus ensuring multi-agent based protections scheme.

C. SMART GRID MONITOR AND DIAGNOSIS

Several works have focused on the use of the MAS approach for monitoring and diagnosis of the smart grid. Smart automation with MAS is presented in [103] using IEC 61850 and OPC UA. A number of projects regarding smart grid monitoring employing MAS and ICT have been presented in [104]. For example, a multi-agent system (COMMAS) for condition monitoring of transformers is presented in [105]. UK utility based called Protection Engineering Diagnostic Agent, known as PEDA, is described in [106].

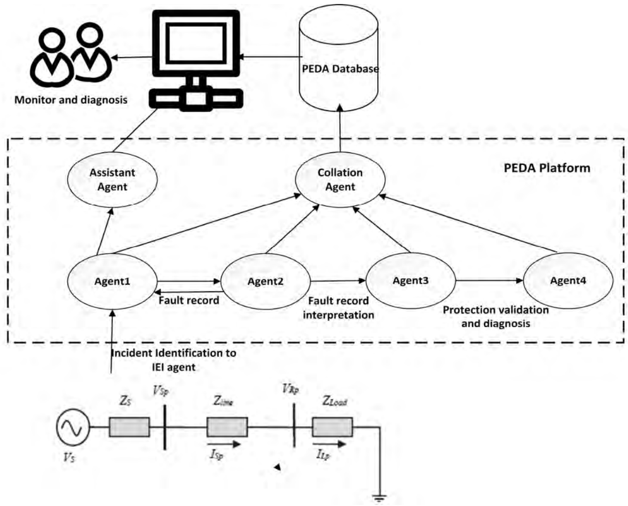

FIGURE 10. PEDA for smart grid monitor and diagnosis.

Fig. 10 presents a general structure of PEDA where a number of agents were deployed (Identifier agent involving event identification, Agent corresponding to fault record acquisition, Agent for fault record assessment, Decision-making agent for fault examination, validation and investigation, SCADA agent for monitoring).

These agents continuously monitor the network, and if any abnormal situation (fault) is identified, it is recorded, interpreted and validated through these agents and collation agent collaborate among all these agents whereas the assistant agent aids with network diagnosis task. Apart from PEDA, several automated agent systems were developed on distributed PLC and Microcontroller board for intelligent monitoring employing IEC 61499/IEC 61450 in literature [107]. Java-based JADE framework has been widely adopted among the researchers for testing of MAS based decentralized intelligent monitoring system [108].

D. SMART GRID TRANSACTIVE ENERGY MANAGEMENT

Transactive energy management is a new edge concept of a smart grid for demand response (DR) management in the electricity market including grid reliability requirements.

It employs coordination (ex: price bidding) between several cognitive entities (ex: consumers, prosumers) in a particular environment thus enabling transactive control mechanism (TCM) [109]. At present, multi-agent technologies are dominating in demand response domain because of their flexibility, decentralized nature, robustness, autonomy and open architecture. There are a number of works found in the domain of MAS based TCM [110], [111]. In other words, the multi-agent platform have all the capabilities to satisfy all the attributes of TCM (flexibility, bidding, empowerment, autonomy, and connectivity). According to smart grid definition, active buyers and sellers take part in the Electricity market (EM) to trade electricity through supply and demand criteria. Many entities such as distribution system operators (DSOs), transmission system operators (TSOs), retailers, aggregators, regulators, consumers, prosumers, etc. are defined in this market with the ability to negotiate, bid, coordinate, and compete. ''Game Theory'' based decision-making process [112], [113], MAS based market (EM) modeling focusing strategic competition [114], bidding strategies [115], and market tariff pricing through market share optimization [116] are some of the highlighted works in the field of electricity market modeling. However, none of them have mentioned the required ICT structure for this market mechanism. To comply with smart grid ICT requirement, Transactive Energy Management and control utilizing peer-to-peer (P2P) energy trading and the required ICT framework have been focused in [117]. A detailed survey on residential demand-side management architecture was presented in [118]. A thorough review of agent-based modeling and simulation of the smart electricity grid is highlighted in [119].

A MAS-based solution including service-oriented architecture (SOA) and IEC 61850 structure is briefly mentioned in [120]. A number of tools that are utilized for agent-based demand response strategy is mentioned in [121] including GridLAB-D [122], OpenDSS [123], AMES [124] and MATLAB/SIMULINK incorporating JADE [125]. A significant work [126] that have summarized ICT enabled MAS based Electricity market, and demand response works is the PowerMatcher [127] which is depicted in Fig. 11. The PowerMatcher [128] is a distributed market control mechanism utilizing supply and demand matching (SDM) in the electricity market.

The implementation of Power Matcher [129] is an ideal example of MAS and ICT based smart grid transactive energy management where many intelligent agents exist (Device agent, Concentrator agent, Auctioneer agent, and unique Objective agent). All the physical devices are classified as device agent (DERS, household appliances), and they send bids and receive prices whereas the concentrator agent aggregates all bids from the sub-cluster of device agents and publishes a single bid towards the auctioneer agent. On top of the hierarchy, the bids from all agents are aggregated by the auctioneer agent and combined into a single bid. Finally, the objective agent played a vital role

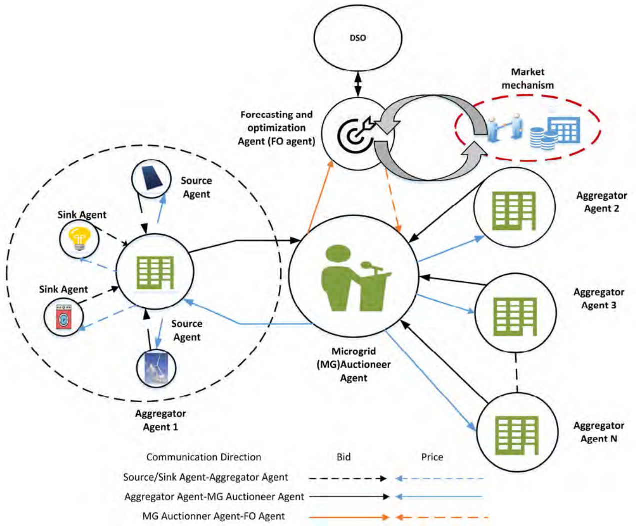

FIGURE 11. PowerMatcher agent cluster mechanism.

by providing purposes to the clusters and interfacing the agent clusters to the business logic based on specific market approach.

E. SMART GRID SECURITY

With the rapid development of the smart grid, it also introduces new security concerns. As electrical infrastructure is now integrating with ICT structure, the electrical grid has been transformed into a Cyber-Physical network where the physical layer consists of power generation, transmission and distribution units and the cyber layer comprises of communication protocols and data exchange for controlling the physical layer. Hence, the grid has always the possibility of security threats from hackers. There was a number of attacks on the EU electrical grid where hackers intended to disrupt the services [130].

The security threats for smart grids are categorized into two segments mainly technical (device failure, cyber threat) and non-technical threat (regulatory policy) respectively in [131]. A number of security threats are presented in Fig. 12 classifying into different categories such as global, local, data, control and device focusing substation automation system architecture. Similarly, in [132], all possible cyber-attacks and challenges in the smart grid are summarized in brief.

A number of approaches have been mentioned in [133], [134] to ensure smart grid security. In order to protect the smart grid against cyber-attacks, a novel security agents based framework is described in [135]. Another multi-agent based approach focusing on SCADA network threat is presented in [136] including real-time testbed implementation. In [137], trust-based multi-agent scheme was employed to prevent false data injection into the smart grid. To analyze cyber security prospect in the smart grid arena, several cyber-physical system (CPS) testbed have been implemented. These test beds focus on three prospects of the

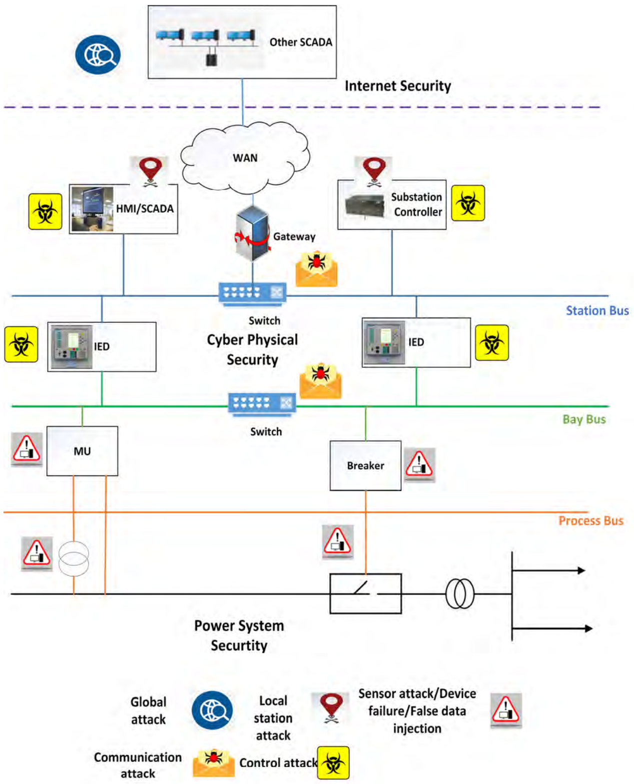

FIGURE 12. Smart grid security threat type.

smart grid security level of vulnerability, effect analysis; and attack-defense mechanism evaluation and validation respectively. Some cyber-physical test bed focusing on cyber security goals and that are found in the literature are summarized in the Table 5.

VII. MULTI-AGENT FRAMEWORK: CURRENT FORM AND NECESSITY

A number of approaches have been investigated in the literature to develop a multi-agent framework in the context of the smart grid. There are numerous reasons behind the necessity for developing such a framework. The scope is to create a suitable technological environment to implement a decentralized, automated, intelligent and resilient power grid according to the different communication and ICT standards proposed by IEEE and IEC. The technical aspects and implementation challenges of MAS have been addressed by researchers and industries together and have been continuing to be subject of research interest for years. Among them, a wide range of technical difficulties have been explored such as data interoperability, high speed data rate, linking power domain with communication domain, performance of different platforms, etc. Additionally, a hierarchy of controls awaits still to be designed for the successful implementation of the MAS integrated ICT enabled smart grid. The details of these potential designs have been discussed in detail in previous sections (i.e. MAS design approach, MAS platform, MAS standards, IEC 61850). A typical form of multi-agent enabled

TABLE 5. MAS and ICT application focusing smart grid security in CPS available in the literature.

Research Institute	Feature	Implementation
University of Arizona-TASSCS [138]	SCADA security systems for smart grid security adopting methods such as detection rate, false alerts, and effectiveness of the protection techniques	RTUs and PLCs utilizing Modbus and DNP3 protocols integrated with a power system simulator and OPNET software
University College Dublin (UCD) [139]	cyber-physical system combining power system simulator and substation automation platform adopting Cyber security intrusion and anomaly detection methods	IEC 61850 standard with DIgSILENT simulator and (OPC) communication protocol
Mississippi State University SCADA Security Laboratory [140]	Cyber-physical testbed for industrial infrastructure to analyze vulnerabilities in the process.	RTDS, OSISoft, and substation GPS clock. Standard communication protocols including Modbus, DNP3, GOOSE and IEEE Std. C37.118
Iowa State University (ISU) [141]	power system simulation including WAN and cyber-attack analysis	RTDS and DIgSILENT based Implementation
Queen's University Belfast- IEC 61850 Cybersecurity Testbed [142]	Testbed for IEC 61850 and its risk and vulnerabilities analysis	RTDS and IEDs and merging units (MU) with IEC 61850 standard protocols (SV,MMS, GOOSE, PTP, SNTP)
Washington State University (WSU)[143]	HIL (hardware in loop) based testbed with smart transmission and distribution system, DER, AMI, and EMS. Different types of cyber security can be analyzed.	Implemented communication platform including DNP 3.0, IEC 61850, ANSI C12.19 and IEEE C37.118 respectively.
Florida International University (FIU) [144]	Smart grid test bed with the implementation of MAS and ICT infrastructure. Cyber Security analysis available.	DNP3, Modbus, IEC 61850 GOOSE, IEC 60870-5-101/104, LG 8979, SES-92, IEEE C37.118). DER, DDS, EMS, EV

smart grid frame work studied in current literature [13], [145] is highlighted in Fig. 13.

Despite the identified advantages of this MAS enabled power grid framework, only few works report on how to perform real time simulations that incorporate ICT standards in the smart grid. The reason is that, it requires complex system design, fast computation algorithms as well as advanced network and telecommunication based technological approaches and protocols (i.e. Optical fiber, IEC 61850). In this regards, the aim of this paper is to propose a laboratory framework

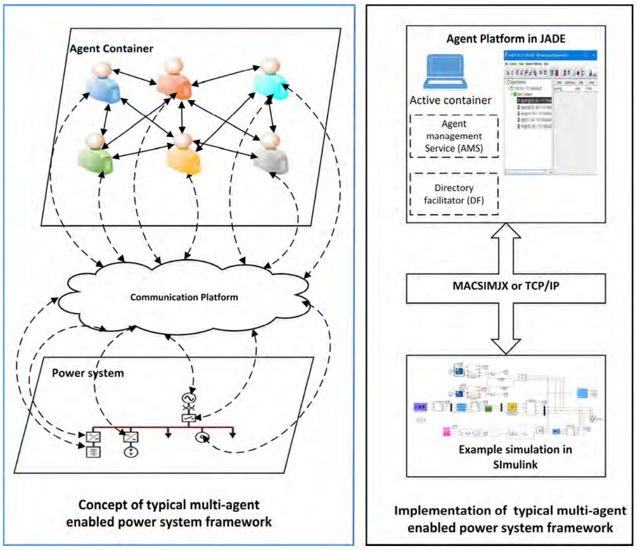

FIGURE 13. Current form of multi-agent enabled smart grid frame.

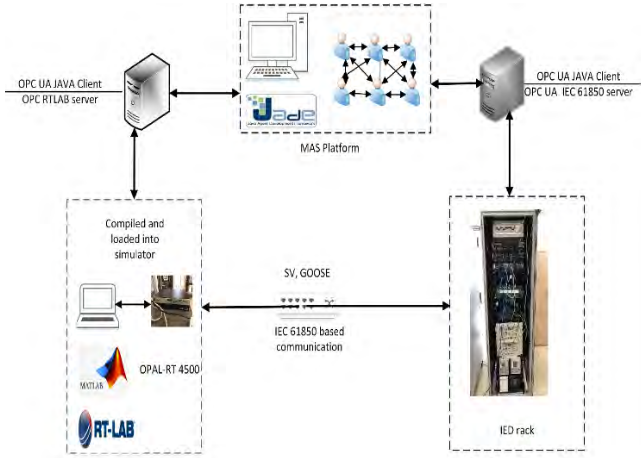

FIGURE 14. Smart grid ICT and IEC 61850 laboratory framework in Curtin.

in ICT enabled smart grid employing multi-agent systems embedded in the IEC 61850 standard. Future work will focus on the hierarchical control system as well as smart strategies for the protection of grid. These works should also take into consideration some of the cyber physical aspects of the grid such as false tripping and bad data detection for available communication networks operating under some software architecture.

VIII. LABORATORY FRAMEWORK

In this section, the authors attempt to describe the preliminary work carried out for the development platform of a testbed for MAS application in ICT enabled smart grid at Curtin University IEC 61850 laboratory. This laboratory features smart grid testing facility with 23 IEDs, from commercial vendors like ABB, Siemens, Alstom, Schneider, and others. The laboratory's architecture, testing facility including the hardware configuration and software implementation, and some of its components will be highlighted in this section. The architecture of this test bed is classified into three stages and can be called a Cyber-Physical System (CPS) altogether altogether and illustrated in Fig. 14. This platform will be used to implement the hierarchical control of smart grid employing IEC 61850.

The first stage comprises physical power systems components based on Real Time Hardware in Loop (RT HIL) via OPAL-RT's RT-LAB simulator. This stage also consists of configuration of industry provided Intelligent Electronic Devices (IEDs) which is vital for Substation Automation System (SAS). The second stage enables the implementation of MAS control in JADE platform. The third stage resolves the interfacing challenge between different components utilizing industry recommended protocols. Additionally, it facilitates the simulation of the network topology, analysis of relevant service quality, and analysis of cyber security and threats through OPNET Modeler communication simulator.

A. POWER SYSTEM NETWORK

The platform features the simulation provision of typical power system including MATLAB/SIMULINK simulation platforms. In addition to that, for Real Time Hardware in Loop (RT HIL) testing, Real-time simulator (RTS) OPAL-RT OP4500 is utilized. Several protection features of IEDs from different commercial vendors are investigated in the real time employing RTLAB Opal-RT. Curtin Green Electric Energy Park (GEEP) facilities can be remotely accessed from IEC 61850 lab to implement hierarchical control. The power system simulation platform is connected to the Intelligent Electronic Devices (IEDs), through standard communication protocols IEC 61850, GOOSE and SV, and standard I/Os respectively.

B. MAS PLATFORM

In this testbed, MAS based platform is implemented in JADE software. This software platform features JADE utility agents and services such as Directory facilitator (DF) agent, Agent Management Services (AMS) agent, and Message Transport Service (MTS). The software platform is set up in compliance with FIPA (foundation for physical intelligent agents) standards to facilitate multi-agent features.

C. COMMUNICATION PLATFORM

Communication platform aims to connect all the components in the system as per different industry standards. While the grid is simulated in real-time employing the Sim Power Systems block set and the ARTEMiS blockset in OPAL-RT respectively, the Agent blocks and the simulated grid interact through TCP/IP network over OPC-RTLAB server. Additionally, OPC/UA server was utilized to connect physical IEDs and MAS platform. Ethernet-based IEC61850 communication protocol facilities real time communication between different IEDS and OPAL-RT OP4500.

IX. CONCLUSION

Due to the highly complicated nature and new energy technology, smart grid concept is evolving very rapidly. The wide spread deployment of smart grid requires developers to handle a large amount of data and information among many parties ensuring reliable, resilient and secured electric grid operation. In this regard, MAS application lends itself as one of the leading technologies because of its decentralized nature and operational robustness. On the other hand, information and communication technology (ICT) transforms conventional ‘‘power grid’’ into a ‘‘smarter’’ one and enables device integration, information exchange, data interoperability, and two-way communication. In this context, the standard communication protocol is an essential criterion for interfacing MAS based platform and the smart electric power grid. This paper attempts to provide an up to date technology status update on MAS applications with the required communication platform in the field of the smart grid. Initially focusing on different aspects of MAS, MAS definition, and MAS development platform moving onto standard communication protocols including ICT infrastructure for the smart grid are described. Along with MAS and ICT integration, a particular attention has been provided on the substation automation system (SAS) employing IEC 61850 including a laboratory conceptual framework. Finally, results of a detailed literature review has been presented highlighting MAS and smart grid ICT application in various areas. The authors hope that future research will benefit from this rigorous, comprehensive and up to date review both in terms of SWOT analysis (strengths, weaknesses, opportunities, and threats) of previously published papers and ready referencing in this rapidly developing field.

REFERENCES

[1] M. Hashmi, S. Hänninen, and K. Mäki, ‘‘Survey of smart grid concepts, architectures, and technological demonstrations worldwide,’’ in *Proc. IEEE PES Conf. Innov. Smart Grid Technol. Latin Amer. (ISGT LA)*, Oct. 2011, pp. 1–7.

[2] L. Ribeiro, J. Barata, and P. Mendes, ‘‘MAS and SOA: Complementary automation paradigms,’’ in *Innovation in Manufacturing Networks*. Boston, MA, USA; Springer, 2008, pp. 259–268.

[3] S. D. J. McArthur, E. M. Davidson, V. M. Catterson, A. L. Dimeas, N. D. Hatziargyriou, F. Ponci, and T. Funabashi, ‘‘Multi-agent systems for power engineering applications—Part 2: Technologies, standards and tools for building multi-agent systems,’’ *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 1753–1759, Oct. 2007.

[4] S. D. J. McArthur and E. M. Davidson, ‘‘Concepts and approaches in multi-agent systems for power applications,’’ in *Proc. 13th Int. Conf., Intell. Syst. Appl. Power Syst.*, Nov. 2005, p. 5.

[5] A. L. Dimeas and N. D. Hatziargyriou, ‘‘Operation of a multiagent system for microgrid control,’’ *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1447–1455, Aug. 2005.

[6] I. S. Baxevanos and D. P. Labridis, ‘‘Implementing multiagent systems technology for power distribution network control and protection management,’’ *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 433–443, Jan. 2007.

[7] I. Walter and F. Gomide, ‘‘Electricity market simulation: Multiagent system approach,’’ in *Proc. ACM Symp. Appl. Comput.*, 2008, pp. 34–38.

[8] M. S. Rahman, M. A. Mahmud, A. M. T. Oo, H. R. Pota, and M. J. Hossain, ‘‘Agent-based reactive power management of power distribution networks with distributed energy generation,’’ *Energy Convers. Manage.*, vol. 120, pp. 120–134, Jul. 2016.

[9] C. M. Colson and M. H. Nehrir, ‘‘Comprehensive real-time microgrid power management and control with distributed agents,’’ *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 617–627, Mar. 2013.

[10] Z.-J. Wu and M.-Q. Hu, ‘‘Research on a substation automation system based on IEC 61850,’’ *Power System Technol.*, vol. 10, p. 17, 2003.

[11] M. H. Moradi, S. Razini, and S. M. Hosseinian, ‘‘State of art of multiagent systems in power engineering: A review,’’ *Renew. Sustain. Energy Rev.*, vol. 58, pp. 814–824, May 2016.

[12] A. L. Kulasekera, R. A. R. C. Gopura, K. T. M. U. Hemapala, and N. Perera, ‘‘A review on multi-agent systems in microgrid applications,’’ in *Proc. IEEE PES Innov. Smart Grid Technol.-India (ISGT)*, Dec. 2011, pp. 173–177.

[13] G. H. Merabet, M. Essaaidi, H. Talei, M. R. Abid, N. Khalil, M. Madkour, and D. Benhaddou, ‘‘Applications of multi-agent systems in smart grids: A survey,’’ in *Proc. Int. Conf. Multimedia Comput. Syst. (ICMCS)*, Apr. 2014, pp. 1088–1094.

[14] V. N. Coelho, M. W. Cohen, I. M. Coelho, N. Liu, and F. G. Guimarães, ‘‘Multi-agent systems applied for energy systems integration: State-of-the-art applications and trends in microgrids,’’ *Appl. Energy*, vol. 187, pp. 820–832, Feb. 2017.

[15] S. Abar, G. K. Theodoropoulos, P. Lemarinier, and G. M. P. O’Hare, ‘‘Agent based modelling and simulation tools: A review of the state-of-art software,’’ *Comput. Sci. Rev.*, vol. 24, pp. 13–33, May 2017.

[16] Z. Zhou, W. K. Chan, and J. H. Chow, ‘‘Agent-based simulation of electricity markets: A survey of tools,’’ *Artif. Intell. Rev.*, vol. 28, no. 4, pp. 305–342, 2007.

[17] C. Nikolai and G. Madey, ‘‘Tools of the trade: A survey of various agent based modeling platforms,’’ *J. Artif. Societies Social Simul.*, vol. 12, no. 2, p. 2, 2009.

[18] V. M. Catterson, E. M. Davidson, and S. D. J. McArthur, ‘‘Practical applications of multi-agent systems in electric power systems,’’ *Eur. Trans. Elect. Power*, vol. 22, no. 2, pp. 235–252, 2012.

[19] M. Metzger and G. Polakow, ‘‘A survey on applications of agent technology in industrial process control,’’ *IEEE Trans. Ind. Informat.*, vol. 7, no. 4, pp. 570–581, Nov. 2011.

[20] S. Kakran and S. Chanana, ‘‘Smart operations of smart grids integrated with distributed generation: A review,’’ *Renew. Sustain. Energy Rev.*, vol. 81, pp. 524–535, Jan. 2018.

[21] A. Mohd, E. Ortjohann, A. Schmelter, N. Hamsic, and D. Morton, ‘‘Challenges in integrating distributed energy storage systems into future smart grid,’’ in *Proc. IEEE Int. Symp. Ind. Electron. (ISIE)*, Jun./Jul. 2008, pp. 1627–1632.

[22] A. G. Phadke, H. Volskis, R. M. de Moraes, T. Bi, R. N. Nayak, Y. K. Sehgal, S. Sen, W. Sattinger, E. Martinez, O. Samuelsson, D. Novosel, V. Madani, and Y. A. Kulikov, ‘‘The wide world of wide-area measurement,’’ *IEEE Power Energy Mag.*, vol. 6, no. 5, pp. 52–65, Sep./Oct. 2008.

[23] M. Anjia, Y. Jiaxi, and G. Zhizhong, ‘‘PMU placement and data processing in WAMS that complements SCADA,’’ in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, Jun. 2005, pp. 780–783.

[24] L. M. Putranto, R. Hara, H. Kita, and E. Tanaka, ‘‘Optimal WAMS hybrid configuration for voltage stability monitoring application considering the existence of conventional measurement,’’ *IEEJ Trans. Electr. Electron. Eng.*, vol. 13, no. 1, pp. 65–75, 2018.

[25] S. A. Arefifar, Y. A.-R. I. Mohamed, and T. H. M. EL-Fouly, ‘‘Comprehensive operational planning framework for self-healing control actions in smart distribution grids,’’ *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4192–4200, Nov. 2013.

[26] H. Kanchev, D. Lu, F. Colas, V. Lazarov, and B. Francois, ‘‘Energy management and operational planning of a microgrid with a PV-based active generator for smart grid applications,’’ *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4583–4592, Oct. 2011.

[27] H. Zeynal, M. Eidiani, and D. Yazdanpanah, ‘‘Intelligent substation automation systems for robust operation of smart grids,’’ in *Proc. IEEE Innov. Smart Grid Technol.-Asia (ISGT)*, May 2014, pp. 786–790.

[28] F. Mwasilu, J. J. Justo, E.-K. Kim, T. D. Do, and J.-W. Jung, ‘‘Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration,’’ *Renew. Sustain. Energy Rev.*, vol. 34, pp. 501–516, Jun. 2014.

[29] O. Palizban and K. Kauhaniemi, ‘‘Energy storage systems in modern grids—Matrix of technologies and applications,’’ *J. Energy Storage*, vol. 6, pp. 248–259, May 2016.

[30] P. G. Da Silva, S. Karnouskos, and D. Ilic, "A survey towards understanding residential prosumers in smart grid neighbourhoods," in *Proc. IEEE 3rd PES Innov. Smart Grid Technol. Eur. (ISGT)*, Oct. 2012, pp. 1–8.
[31] P. Samadi, H. Mohsenian-Rad, R. Schober, and V. W. S. Wong, "Advanced demand side management for the future smart grid using mechanism design," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1170–1180, Sep. 2012.
[32] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. P. Hancke, "Smart grid technologies: Communication technologies and standards," *IEEE Trans. Ind. Informat.*, vol. 7, no. 4, pp. 529–539, Nov. 2011.
[33] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. P. Hancke, "A survey on smart grid potential applications and communication requirements," *IEEE Trans. Ind. Informat.*, vol. 9, no. 1, pp. 28–42, Feb. 2013.
[34] S. Muyeen and S. Rahman, *Communication, Control and Security Challenges for the Smart Grid*. Edison, NJ, USA: IET, 2017.
[35] Y. Yan, Y. Qian, H. Sharif, and D. Tipper, "A survey on smart grid communication infrastructures: Motivations, requirements and challenges," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 1, pp. 5–20, 1st Quart., 2013.
[36] S. B. Ghosn, P. Ranganathan, S. Salem, J. Tang, D. Loegering, and K. E. Nygard, "Agent-oriented designs for a self healing smart grid," in *Proc. IEEE 1st Int. Conf. Smart Grid Commun. (SmartGridComm)*, Oct. 2010, pp. 461–466.
[37] S. D. J. McArthur, E. M. Davidson, V. M. Catterson, A. L. Dimeas, N. D. Hatziargyriou, F. Ponci, and T. Funabashi, "Multi-agent systems for power engineering applications—Part I: Concepts, approaches, and technical challenges," *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 1743–1752, Nov. 2007.
[38] Z. Ming, R. Jianwen, L. Gengyin, and X. Xianghai, "A multi-agent based dispatching operation instructing system in electric power systems," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, vol. 1, Jul. 2003, pp. 436–440.
[39] A. Dimeas and N. Hatziargyriou, "A multi-agent system for microgrids," in *Proc. Hellenic Conf. Artif. Intell.* Berlin, Germany: Springer, 2004, pp. 447–455.
[40] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, "Microgrids management," *IEEE Power Energy Mag.*, vol. 6, no. 3, pp. 54–65, May/Jun. 2008.
[41] Z. Wang, R. Yang, and L. Wang, "Intelligent multi-agent control for integrated building and micro-grid systems," in *Proc. IEEE PES Innov. Smart Grid Technol. (ISGT)*, Jan. 2011, pp. 1–7.
[42] J. Zhang, Q. Ai, and X. Wang, "Application of multi-agent system in a microgrid," *Autom. Electr. Power Syst.*, vol. 24, p. 18, Nov. 2008.
[43] H. S. V. S. K. Nunna and S. Doolla, "Multiagent-based distributed-energy-resource management for intelligent microgrids," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1678–1687, Apr. 2013.
[44] A. Kantamneni, L. E. Brown, G. Parker, and W. W. Weaver, "Survey of multi-agent systems for microgrid control," *Eng. Appl. Artif. Intell.*, vol. 45, pp. 192–203, 2015.
[45] Z. Xiao, T. Li, M. Huang, J. Shi, J. Yang, J. Yu, and W. Wu, "Hierarchical MAS based control strategy for microgrid," *Energies*, vol. 3, no. 9, pp. 1622–1638, 2010.
[46] M. Cossentino, C. Lodato, S. Lopes, M. Pucci, G. Vitale, and M. Cirrincione, "A multi-agent architecture for simulating and managing microgrids," in *Proc. Federated Conf. Comput. Sci. Inf. Syst. (FedCSIS)*, Sep. 2011, pp. 619–622.
[47] L. M. Tolbert, H. Qi, and F. Z. Peng, "Scalable multi-agent system for real-time electric power management," in *Proc. Conf. Power Eng. Soc. Summer Meeting.*, vol. 3, Jul. 2001, pp. 1676–1679.
[48] L. Hernandez, C. Baladron, J. M. Aguiar, B. Carro, A. Sanchez-Esguevillas, J. Lloret, D. Chinarro, J. J. Gomez-Sanz, and D. Cook, "A multi-agent system architecture for smart grid management and forecasting of energy demand in virtual power plants," *IEEE Commun. Mag.*, vol. 51, no. 1, pp. 106–113, Jan. 2013.
[49] C. Jonquet, P. Dugénie, and S. A. Cerri, "Service-based integration of grid and multi-agent systems models," in *Proc. Int. Workshop Service-Oriented Comput., Agents, Semantics, Eng.* Berlin, Germany: Springer, 2008, pp. 56–68.
[50] P.-M. Ricordel and Y. Demazeau, "From analysis to deployment: A multi-agent platform survey," in *Proc. Int. Workshop Eng. Societies Agents World*. Berlin, Germany: Springer, 2000, pp. 93–105.
[51] F. Zambonelli, N. R. Jennings, and M. Wooldridge, "Developing multiagent systems: The Gaia methodology," *ACM Trans. Softw. Eng. Methodol.*, vol. 12, no. 3, pp. 317–370, 2003.
[52] A. Omicini, "SODA: Societies and infrastructures in the analysis and design of agent-based systems," in *Proc. Int. Workshop Agent-Oriented Softw. Eng.* Berlin, Germany: Springer, 2000, pp. 185–193.
[53] C. Bădică, Z. Budimac, H.-D. Burkhard, and M. Ivanović, "Software agents: Languages, tools, platforms," *Comput. Sci. Inf. Syst.*, vol. 8, no. 2, pp. 255–298, 2011.
[54] Y. Liang and R. H. Campbell, "Understanding and simulating the IEC 61850 standard," Univ. Illinois Urbana-Champaign, Champaign, IL, USA, Tech. Rep., 2008.
[55] T. Finin, R. Fritzson, D. McKay, and R. McEntire, "KQML as an agent communication language," in *Proc. ACM 3rd Int. Conf. Inf. Knowl. Manage.*, 1994, pp. 456–463.
[56] P. D. O'Brien and R. C. Nicol, "FIPA—Towards a standard for software agents," *BT Technol. J.*, vol. 16, no. 3, pp. 51–59, 1998.
[57] H. Suguri, E. Kodama, M. Miyazaki, H. Nunokawa, and S. Noguchi, "Implementation of FIPA ontology service," in *Proc. Workshop Ontologies Agent Syst., 5th Int. Conf. Auton. Agents*, Montreal, QC, Canada, vol. 30, 2001, pp. 1–8.
[58] T. Basso and R. DeBlasio, "IEEE smart grid series of standards IEEE 2030 (interoperability) and IEEE 1547 (interconnection) status," in *Proc. Grid-Interop*, vol. 2030, 2011, pp. 5–8.
[59] Q.-D. Ho, Y. Gao, G. Rajalingham, and T. Le-Ngoc, "Smart grid communications network (SGCN)," in *Wireless Communications Networks for the Smart Grid*. Cham, Switzerland: Springer, 2014, pp. 15–30.
[60] *Power Utility Automation*, Standard IEC 61850, 2003.
[61] G. Clarke, D. Reynders, and E. Wright, *Practical Modern SCADA Protocols: DNP3, 60870.5 and Related Systems*. Boston, MA, USA: Newnes, 2004
[62] R. E. Mackiewicz, "Overview of IEC 61850 and benefits," in *Proc. IEEE PES Power Syst. Conf. Expo. (PSCE)*, Oct./Nov. 2006, pp. 623–630.
[63] W. Wang and Z. Lu, "Cyber security in the Smart Grid: Survey and challenges," *Computer Netw.*, vol. 57, no. 5, pp. 1344–1371, 2013.
[64] N. Higgins, V. Vyatkin, N.-K. C. Nair, and K. Schwarz, "Distributed power system automation with IEC 61850, IEC 61499, and intelligent control," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 41, no. 1, pp. 81–92, Jan. 2011.
[65] V. Vyatkin, G. Zhabelova, N. Higgins, K. Schwarz, and N.-K. C. Nair, "Towards intelligent smart grid devices with IEC 61850 interoperability and IEC 61499 open control architecture," in *Proc. IEEE PES Transmiss. Distrib. Conf. Expo.*, Apr. 2010, pp. 1–8.
[66] G. Zhabelova and V. Vyatkin, "Multiagent smart grid automation architecture based on IEC 61850/61499 intelligent logical nodes," *IEEE Trans. Ind. Electron.*, vol. 59, no. 5, pp. 2351–2362, May 2012.
[67] L. Andersson, K.-P. Brand, C. Brunner, and W. Wimmer, "Reliability investigations for SA communication architectures based on IEC 61850," in *Proc. IEEE Russia Power Tech*, Jun. 2005, pp. 1–7.
[68] M. G. Kanabar and T. S. Sidhu, "Reliability and availability analysis of IEC 61850 based substation communication architectures," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PES)*, Jul. 2009, pp. 1–8.
[69] A. Pal and R. Dash, "A paradigm shift in substation engineering: IEC 61850 approach," *Procedia Technol.*, vol. 21, pp. 8–14, Nov. 2015.
[70] T. S. Sidhu and Y. Yin, "Modelling and simulation for performance evaluation of IEC61850-based substation communication systems," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1482–1489, Jul. 2007.
[71] Y.-L. Li, Z.-X. Yuan, B. Chen, R. Su, and L.-M. Wang, "Analysis and implementation of TCP/TP based specific communication service mapping MMS in IEC 61850," *Power Syst. Technol.*, vol. 24, p. 10, 2004.
[72] Z.-L. Yin, W.-S. Liu, Q.-X. Yang, and Y.-L. Qin, "Generic substation event model based on IEC 61850," *Automat. Electr. Power Syst.*, vol. 29, no. 19, pp. 45–50, 2005.
[73] D. Hou and D. Dolezilek, *What it Can and Cannot Offer to Traditional Protection Schemes*, Standard IEC 61850, Schweitzer Eng. Lab., 2008.
[74] D. M. E. Ingram, P. Schaub, and D. A. Campbell, "Use of precision time protocol to synchronize sampled-value process buses," *IEEE Trans. Instrum. Meas.*, vol. 61, no. 5, pp. 1173–1180, May 2012.
[75] V. Dehalwar, A. Kalam, M. L. Kolhe, and A. Zayegh, "Review of IEEE 802.22 and IEC 61850 for real-time communication in Smart Grid," in *Proc. Int. Conf. Comput. Netw. Commun. (CoCoNet)*, Dec. 2015, pp. 571–575.
[76] I. Xyngi and M. Popov, "IEC61850 overview—Where protection meets communication," in *Proc. IET 10th Int. Conf. Develop. Power Syst. Protection (DPSP)*, Mar./Apr. 2010, pp. 1–5.

[77] D. Baigent, M. Adamiak, R. Mackiewicz, and G. M. G. M. Sisco, "IEC 61850 communication networks and systems in substations: An overview for users," in *Proc. SISCO Syst.*, vol. 3, 2004, pp 61–68.
[78] M. Pipattanasomporn, H. Feroze, and S. Rahman, "Multi-agent systems in a distributed smart grid: Design and implementation," in *Proc. IEEE/PES Power Syst. Conf. Expo. (PSCE)*, Mar. 2009, pp. 1–8.
[79] F. Daneshfar and H. Bevrani, "Load-frequency control: A GA-based multi-agent reinforcement learning," *IET Gener., Transmiss. Distrib.*, vol. 4, no. 1, pp. 13–26, Jan. 2010.
[80] V. P. Singh, N. Kishor, and P. Samuel, "Distributed multi-agent system-based load frequency control for multi-area power system in smart grid," *IEEE Trans. Ind. Electron.*, vol. 64, no. 6, pp. 5151–5160, Jun. 2017.
[81] A. A. Hamad, H. E. Farag, and E. F. El-Saadany, "A novel multiagent control scheme for voltage regulation in DC distribution systems," *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 534–545, Apr. 2015.
[82] H. E. Z. Farag, E. F. El-Saadany, and R. Seethapathy, "A two ways communication-based distributed control for voltage regulation in smart distribution feeders," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 271–281, Mar. 2012.
[83] S. Saxena, N. A. El-Taweel, H. E. Farag, and L. S. Hilaire, "Design and field implementation of a multi-agent system for voltage regulation using smart inverters and data distribution service (DDS)," in *Proc. IEEE Elect. Power Energy Conf. (EPEC)*, Oct. 2018, pp. 1–6.
[84] M. H. Cintuglu, H. Martin, and O. A. Mohammed, "An intelligent multi agent framework for active distribution networks based on IEC 61850 and FIPA standards," in *Proc. 18th Int. Conf. Intell. Syst. Appl. Power Syst. (ISAP)*, Sep. 2015, pp. 1–6.
[85] M. H. Cintuglu, T. Youssef, and O. A. Mohammed, "Development and application of a real-time testbed for multiagent system interoperability: A case study on hierarchical microgrid control," *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 1759–1768, May 2018.
[86] H.-M. Kim, T. Kinoshita, and M.-C. Shin, "A multiagent system for autonomous operation of islanded microgrids based on a power market environment," *Energies*, vol. 3, no. 12, pp. 1972–1990, 2010.
[87] S. T. Cha, Q. Wu, J. Østergaard, and A. Saleem, "Multi-agent based controller for islanding operation of active distribution networks with distributed generation (DG)," in *Proc. 4th Int. Conf. Electr. Utility Deregulation Restructuring Power Technol. (DRPT)*, Jul. 2011, pp. 803–810.
[88] M. Manbachi, M. Nasri, B. Shahabi, H. Farhangi, A. Palizban, S. Arzanpour, M. Moallem, and D. C. Lee, "Real-time adaptive VVO/CVR topology using multi-agent system and IEC 61850-based communication protocol," *IEEE Trans. Sustain. Energy*, vol. 5, no. 2, pp. 587–597, Apr. 2014.
[89] M. Manbachi, A. Sadu, H. Farhangi, A. Monti, A. Palizban, F. Ponci, and S. Arzanpour, "Real-time co-simulation platform for smart grid volt-VAR optimization using IEC 61850," *IEEE Trans. Ind. Informat.*, vol. 12, no. 4, pp. 1392–1402, Aug. 2016.
[90] M. Eriksson, M. Armendariz, O. O. Vasilenko, A. Saleem, and L. Nordström, "Multiagent-based distribution automation solution for self-healing grids," *IEEE Trans. Ind. Electron.*, vol. 62, no. 4, pp. 2620–2628, Apr. 2015.
[91] E. Shirazi and S. Jadid, "Autonomous self-healing in smart distribution grids using multi agent systems," *IEEE Trans. Ind. Informat.*, to be published.
[92] E. M. Davidson, M. J. Dolan, G. W. Ault, and S. D. J. McArthur, "AuRA-NMS: An autonomous regional active network management system for EDF energy and SP energy networks," in *Proc. IEEE PES Gen. Meeting*, Jul. 2010, pp. 1–6.
[93] D. Pala, C. Tornelli, and G. Proserpio, "An adaptive, agent-based protection scheme for radial distribution networks based on IEC 61850 and IEC 61499," in *Proc. Integr. Renewables Distrib. Grid Workshop (CIRED)*, May 2012, pp. 1–4.
[94] M. H. Cintuglu, T. Ma, and O. A. Mohammed, "Protection of autonomous microgrids using agent-based distributed communication," *IEEE Trans. Power Del.*, vol. 32, no. 1, pp. 351–360, Feb. 2017.
[95] M. S. Rahman, M. A. Mahmud, H. R. Pota, and M. J. Hossain, "A multi-agent approach for enhancing transient stability of smart grids," *Int. J. Elect. Power Energy Syst.*, vol. 67, pp. 488–500, May 2015.
[96] J. B. Leite and J. R. S. Mantovani, "Development of a self-healing strategy with multiagent systems for distribution networks," *IEEE Trans. Smart Grid*, vol. 8, no. 5, pp. 2198–2206, Sep. 2017.
[97] N. Kashyap, C. W. Yang, S. Sierla, and P. G. Flikkema, "Automated fault location and isolation in distribution grids with distributed control and unreliable communication," *IEEE Trans. Ind. Electron.*, vol. 62, no. 4, pp. 2612–2619, Apr. 2015.
[98] S. Chouhan, J. Ghorbani, H. Inan, A. Feliachi, and M. A. Choudhry, "Smart MAS restoration for distribution system with microgrids," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PES)*, Jul. 2013, pp. 1–5.
[99] A. Zidan and E. F. El-Saadany, "A cooperative multiagent framework for self-healing mechanisms in distribution systems," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1525–1539, Sep. 2012.
[100] H. S. Samkari and B. K. Johnson, "Multi-agent protection scheme for resilient microgrid systems with aggregated electronically coupled distributed energy resources," in *Proc. IEEE 44th Annu. Conf. Ind. Electron. Soc. (IECON)*, Oct. 2018, pp. 752–757.
[101] A. E. B. Abu-Elanien, M. M. A. Salama, and K. B. Shaban, "Modern network reconfiguration techniques for service restoration in distribution systems: A step to a smarter grid," *Alexandria Eng. J.*, vol. 57, no. 4, pp. 3959–3967, 2018.
[102] A. Saleem, N. Honeth, and L. Nordström, "A case study of multi-agent interoperability in IEC 61850 environments," in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. Eur. (ISGT)*, Oct. 2010, pp. 1–8.
[103] S. Srinivasan, R. Kumar, and J. Vain, "Integration of IEC 61850 and OPC UA for Smart Grid automation," in *Proc. IEEE Innov. Smart Grid Technol.-Asia (ISGT)*, Nov. 2013, pp. 1–5.
[104] P. Leitão, P. Vrba, and T. Strasser, "Multi-agent systems as automation platform for intelligent energy systems," in *Proc. IEEE 39th Annu. Conf. Ind. Electron. Soc. (IECON)*, Nov. 2013, pp. 66–71.
[105] S. D. J. McArthur and E. M. Davidson, "Multi-agent systems for diagnostic and condition monitoring applications," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, Jun. 2004, pp. 50–54.
[106] S. D. McArthur, E. M. Davidson, J. A. Hossack, and J. R. McDonald, "Automating power system fault diagnosis through multi-agent system technology," in *Proc. 37th Annu. Hawaii Int. Conf. Syst. Sci.*, Jan. 2004, p. 8.
[107] C.-H. Yang, G. Zhabelova, C.-W. Yang, and V. Vyatkin, "Cosimulation environment for event-driven distributed controls of smart grid," *IEEE Trans. Ind. Informat.*, vol. 9, no. 3, pp. 1423–1435, Aug. 2013.
[108] S. J. Chatzivasiliadis, N. D. Hatziargyriou, and A. L. Dimeas, "Development of an agent based intelligent control system for microgrids," in *Proc. IEEE Power and Energy Soc. Gen. Meeting-21st Century Convers. Del. Elect. Energy*, Jul. 2008, pp. 1–6.
[109] D. Forfia, M. Knight, and R. Melton, "The view from the top of the mountain: Building a community of practice with the GridWise transactive energy framework," *IEEE Power Energy Mag.*, vol. 14, no. 3, pp. 25–33, Apr. 2016.
[110] E. Karfopoulos, L. Tena, A. Torres, P. Salas, J. G. Jorda, A. Dimeas, and N. Hatziargyriou, "A multi-agent system providing demand response services from residential consumers," *Electr. Power Syst. Res.*, vol. 120, pp. 163–176, Mar. 2015.
[111] V. Bui, A. Hussain, and H.-M. Kim, "A multiagent-based hierarchical energy management strategy for multi-microgrids considering adjustable power and demand response," *IEEE Trans. Smart Grid*, vol. 9, no. 2, pp. 1323–1333, Mar. 2018.
[112] Z. Ma, D. S. Callaway, and I. A. Hiskens, "Decentralized charging control of large populations of plug-in electric vehicles," *IEEE Trans. Control Syst. Technol.*, vol. 21, no. 1, pp. 67–78, Jan. 2013.
[113] Y. S. Son, R. Baldick, K.-H. Lee, and S. Siddiqi, "Short-term electricity market auction game analysis: Uniform and pay-as-bid pricing," *IEEE Trans. Power Syst.*, vol. 19, no. 4, pp. 1990–1998, Nov. 2004.
[114] M. Shafie-Khah and J. P. Catalão, "A stochastic multi-layer agent-based model to study electricity market participants behavior," *IEEE Trans. Power Syst.*, vol. 30, no. 2, pp. 867–881, Mar. 2015.
[115] B. Ramachandran, S. K. Srivastava, C. S. Edrington, and D. A. Cartes, "An intelligent auction scheme for smart grid market using a hybrid immune algorithm," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4603–4612, Oct. 2011.
[116] R. T. Kuate, M. Chli, and H. H. Wang, "Optimising market share and profit margin: Smdp-based tariff pricing under the smart grid paradigm," in *Proc. IEEE PES Innov. Smart Grid Technol., Eur. (ISGT)*, Oct. 2014, pp. 1–6.

[117] O. Jogunola, A. Ikpehai, K. Anoh, B. Adebisi, M. Hammoudeh, S.-Y. Son, and G. Harris, "State-of-the-art and prospects for peer-to-peer transaction-based energy system," *Energies*, vol. 10, no. 12, p. 2106, 2017.

[118] B. P. Esther and K. S. Kumar, "A survey on residential demand side management architecture, approaches, optimization models and methods," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 342–351, Jun. 2016.

[119] P. Ringler, D. Keles, and W. Fichtner, "Agent-based modelling and simulation of smart electricity grids and markets—A literature review," *Renew. Sustain. Energy Rev.*, vol. 57, pp. 205–215, May 2016.

[120] T. Strasser, "A review of architectures and concepts for intelligence in future electric energy systems," *IEEE Trans. Ind. Electron.*, vol. 62, no. 4, pp. 2424–2438, Apr. 2015.

[121] H. A. Li and N.-K. C. Nair, "Multi-agent systems and demand response: A systematic review," in *Proc. Australas. Universities Power Eng. Conf. (AUPEC)*, Sep. 2015, pp. 1–6.

[122] S. Li, D. Zhang, A. B. Roget, and Z. O'Neill, "Integrating home energy simulation and dynamic electricity price for demand response study," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 779–788, Mar. 2014.

[123] V. J. Gutierrez-Martinez, E. A. Zamora-Cardenas, A. Pizano-Martinez, J. M. Lozano-Garcia, and M. A. Gomez-Martinez, "Optimal dispatch model for demand response aggregators," *J. Elect. Eng. Technol.*, vol. 14, no. 1, pp. 85–96, 2019.

[124] E. Guerci, M. A. Rastegar, and S. Cincotti, "Agent-based modeling and simulation of competitive wholesale electricity markets," in *Handbook of Power Systems II*. Berlin, Germany: Springer, 2010, pp. 241–286.

[125] M. Meiqin, D. Wei, and L. Chang, "Design of a novel simulation platform for the EMS-MG based on MAS," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2011, pp. 2670–2675.

[126] P. Vrba, V. Marík, P. Siano, P. Leitão, G. Zhabelova, and V. V. T. Strasser, "A review of agent and service-oriented concepts applied to intelligent energy systems," *IEEE Trans. Ind. Informat.*, vol. 10, no. 3, pp. 1890–1903, Aug. 2014.

[127] K. Kok, G. Venekamp, and P. Macdougall, "Market-based control in decentralized electrical power systems," in *Proc. 1st Int. Workshop Agent Technol. Energy Syst. (ATES)*, Toronto, ON, Canada, 2010, pp. 1–6.

[128] F. Bliek, A. van den Noort, B. Roossien, R. Kamphuis, J. de Wit, J. van der Velde, and M. Eijgelaar, "PowerMatching City, a living lab smart grid demonstration," in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. Eur. (ISGT)*, Oct. 2010, pp. 1–8.

[129] J. Kok, "The powermatcher: Smart coordination for the smart electricity grid," TNO, Soesterberg, The Netherlands, SIKS Dissertation Series 2013-17, 2013.

[130] A. Gurzu, *Hackers Threaten Smart Power Grids*. Boston, MA, USA: Politico, 2018.

[131] A. O. Otuoze, M. W. Mustafa, and R. M. Larik, "Smart grids security challenges: Classification by sources of threats," *J. Elect. Syst. Inf. Technol.*, vol. 5, no. 3, pp. 468–483, 2018.

[132] X. Li, X. Liang, R. Lu, X. Shen, X. Lin, and H. Zhu, "Securing smart grid: Cyber attacks, countermeasures, and challenges," *IEEE Commun. Mag.*, vol. 50, no. 8, pp. 38–45, Aug. 2012.

[133] K. Moslehi and R. Kumar, "A reliability perspective of the smart grid," *IEEE Trans. Smart Grid*, vol. 1, no. 1, pp. 57–64, Jun. 2010.

[134] A. Sanjab, W. Saad, I. Guvenc, A. Sarwat, and S. Biswas, "Smart grid security: Threats, challenges, and solutions," 2016, *arXiv:1606.06992*. [Online]. Available: https://arxiv.org/abs/1606.06992

[135] D. Wei, Y. Lu, M. Jafari, P. Skare, and K. Rohde, "An integrated security system of protecting smart grid against cyber attacks," in *Proc. Innov. Smart Grid Technol. (ISGT)*, Jan. 2010, pp. 1–7.

[136] Y. Atif, Y. Jiang, B. Lindström, J. Ding, M. Jeusfeld, S. Andler, E. Nero, C. Brax, and D. Haglund, *Multi-Agent Systems for Power Grid Monitoring: Technical Report for Package 4.1 of ELVIRA Project*. Univ. Skövde, Skövde, Sweden, 2018.

[137] I. Matei, J. S. Baras, and V. Srinivasan, "Trust-based multi-agent filtering for increased smart grid security," in *Proc. 20th Medit. Conf. Control Automat. (MED)*, Jul. 2012, pp. 716–721.

[138] M. Mallouhi, Y. Al-Nashif, D. Cox, T. Chadaga, and S. Hariri, "A testbed for analyzing security of SCADA control systems (TASSCS)," in *Proc. IEEE PES Innov. Smart Grid Technol. (ISGT)*, Sep. 2011, pp. 1–7.

[139] J. Hong, S.-S. Wu, A. Stefanov, A. Fshosha, C.-C. Liu, P. Gladyshev, M. Govindarasu, "An intrusion and defense testbed in a cyber-power system environment," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2011, pp. 1–5.

[140] T. Morris, A. Srivastava, B. Reaves, W. Gao, K. Pavurapu, and R. Reddi, "A control system testbed to validate critical infrastructure protection concepts," *Int. J. Crit. Infrastruct. Protection*, vol. 4, no. 2, pp. 88–103, 2011.

[141] A. Hahn, A. Ashok, S. Sridhar, and M. Govindarasu, "Cyber-physical security testbeds: Architecture, application, and evaluation for smart grid," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 847–855, Jun. 2013.

[142] Y. Yang, H. T. Jiang, K. McLaughlin, L. Gao, Y. B. Yuan, W. Huang, and S. Sezer, "Cybersecurity test-bed for IEC 61850 based smart substations," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2015, pp. 1–5.

[143] C.-C. Sun, J. Hong, and C.-C. Liu, "A co-simulation environment for integrated cyber and power systems," in *Proc. IEEE Int. Conf. Smart Grid Commun. (SmartGridComm)*, Nov. 2015, pp. 133–138.

[144] M. H. Cintuglu, O. A. Mohammed, K. Akkaya, and A. S. Uluagac, "A survey on smart grid cyber-physical system testbeds," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 446–464, 1st Quart., 2017.

[145] M. Nasri, "RCPC: A multi-agent system for coordinated control of power electronic converters in microgrids," Ph.D. dissertation, Appl. Sci., School Mechtron. Syst. Eng., 2016.

MOHAMMAD HASANUZZAMAN SHAWON (S'11) received the B.Sc. degree from the Islamic University of Technology, Bangladesh, and the M.Sc. degree from The Petroleum Institute, Abu Dhabi, UAE, in 2012. He is currently pursuing the Ph.D. degree in electrical engineering, under the Curtin-Aberdeen Alliance (Jointly hosted by Curtin University, Australia, and the University of Aberdeen, U.K.). His research interests include agent control in smart grid, digital substation automation and protection, and cyber-physical infrastructure in smart grid.

S. M. MUYEEN (S'03–M'08–SM'12) received the B.Sc. Eng. degree from the Rajshahi University of Engineering and Technology (RUET), Bangladesh, formerly known as the Rajshahi Institute of Technology, in 2000, and the M.Eng. and Ph.D. degrees from the Kitami Institute of Technology, Japan, in 2005 and 2008, respectively, all in electrical and electronic engineering. He is currently an Associate Professor with the Department of Electrical and Computer Engineering, Curtin University, Perth, Australia. His research interests are power system stability and control, electrical machine, FACTS, energy storage systems (ESS), Renewable Energy, and HVDC systems. He is a Fellow of Engineers Australia. He has been a Keynote Speaker and an Invited Speaker at many international conferences, workshops, and universities. He has published more than 200 articles in different journals and international conferences. He has published six books as an author or editor. He is serving as an Editor or Associate Editor for many prestigious Journals from the IEEE, IET, and other publishers, including the IEEE Transactions on Sustainable Energy, the IEEE Power Engineering Letters, the *IET Renewable Power Generation*, and the *IET Generation, Transmission & Distribution*.

ARINDAM GHOSH (S'80–M'83–SM'93–F'06) received the Ph.D. degree from the University of Calgary, Calgary, AB, Canada, in 1983. He is currently a Professor with Curtin University, Perth, WA, Australia. Before joining Curtin University, he was with the Queensland University of Technology, Brisbane, QLD, Australia, from 2006 to 2013, and IIT Kanpur, Kanpur, India, from 1985 to 2006. His research interests are renewable energy and distributed generation, microgrids and power electronics applications to power systems. He is a Fellow of the Indian National Academy of Engineering.

SYED MOFIZUL ISLAM received the B.Sc. degree in electrical engineering from the Bangladesh University of Engineering and Technology, Bangladesh, in 1979, and the M.Sc. and Ph.D. degrees in electrical power engineering from the King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, in 1983 and 1988, respectively. Prior to joining Federation University, he was the John Curtin Distinguished Professor in electrical power engineering and the Director of the Centre for Smart Grid and Sustainable Power Systems, Curtin University, Perth, WA, Australia. He was the Dean of the Faculty of Science and Engineering, Curtin University, from 2011 to 2018. He has been a Visiting Professor with the Shanghai University of Electrical Power and Xi'an Jiatong University, China. He is currently the Dean of the School of Science Engineering and Information Technology, Federation University Australia. He has extensive experience in international collaboration in both education and research with institutes and researchers in China and other countries. His research interests include condition monitoring of transformers, wind energy conversion, and smart power systems. He has published over 270 technical papers in his area of expertise. He is a Fellow of the Engineers Australia and the IET, a Senior Member of the IAS, PES, and DEIS, and a Chartered Engineer in U.K., and a Chartered Professional Engineer in Australia. He is a member of the Steering Committee of the Australian Power Institute and the WA EESA Board. He received the Dean's Medallion for research at Curtin University, in 1999, the IEEE T Burke Haye's Faculty Recognition Award, in 2000, the Curtin University Inaugural Award for Research Development, in 2012, and the Sir John Madsen Medal, in 2011 and 2014, respectively, for the Best Electrical Engineering Paper in Australia. He has been a Keynote Speaker and an Invited Speaker at many international workshops and conferences. He was the Guest Editor-in-Chief of the IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, the *Special Issue on Variable Power Generation Integration into Grid*. He is a Founding Editor of the IEEE TRANSACTIONS ON SUSTAINABLE ENERGY and an Associate Editor of the *IET Renewable Power Generation*.

MURILO S. BAPTISTA received the Ph.D. degree from the University of São Paulo, Brazil, on the response of non-linear dynamical systems under external perturbations. He has been a Reader with the University of Aberdeen, since 2014, having joined this University as a Senior Lecturer, in 2009. Before joining UoA, he held a postdoctoral position with the University of Maryland, USA, from 1997 to 1999, the University of São Paulo, Brazil, from 1999 to 2003, the University of Potsdam, Germany, from 2004 to 2006, as a Guest Scientist with the Max-Planck-Institute for the Physics of Complex Systems, Germany, from 2007 to 2008, and as a Guest Assistant Professor with the Centre for Applied Mathematics, University of Oporto, Portugal, from 2008 to 2009. One of his main current themes of research is related to unraveling the complex relationship among information, collective behavior and structure in large and often controlled networked complex systems of dynamical units or agents, such as the power grid, the brain, and other large socio-economic-political systems.