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Review

A survey of smart grid architectures, applications, benefits and standardization

Nazmus S. Nafi*, Khandakar Ahmed, Mark A. Gregory, Manoj Datta

School of Engineering, RMIT University, Australia

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ABSTRACT

The successful transformation of conventional power grids into Smart Grids (SG) will require robust and scalable communication network infrastructure. The SGs will facilitate bidirectional electricity flow, advanced load management, a self-healing protection mechanism and advanced monitoring capabilities to make the power system more energy efficient and reliable. In this paper SG communication network architectures, standardization efforts and details of potential SG applications are identified. The future deployment of real-time or near-real-time SG applications is dependent on the introduction of a SG compatible communication system that includes a communication protocol for cross-domain traffic flows within the SG. This paper identifies the challenges within the cross-functional domains of the power and communication systems that current research aims to overcome. The status of SG related machine to machine communication system design is described and recommendations are provided for diverse new and innovative traffic features.

1. Introduction

In the era of advanced automation and broadband communications where every aspect of daily life can be positively affected by smart applications; our power grids continue to be operated using antiquated technologies and systems. Although the traditional power grid has been an effective solution for more than 50 years, the future is uncertain as the shift from coal and gas to solar and wind occurs. As more efficient and lower cost batteries come onto the market the opportunity for bidirectional electricity flows will grow and the open loop system, where power flows from the generation plant to the customer, will cease to be the norm. Also, a lack of situational awareness, poor visibility and control over the power grid is making it more vulnerable to disturbances such as blackouts and brownouts (The Smart Grid: An Introduction, 2010; Aggarwal et al., 2010). However, there are other pressing issues such as the move to incorporate renewable energy and gradually reduce carbon emissions. In the United States of America power generation produces more than 40% of carbon emissions (Hledik, 2009). Similarly, Australia's total carbon emissions are projected to reach 685 Mt and 801 Mt of CO_2 in 2020 and 2030 respectively, where power generation will be producing 30% of the carbon emissions in both cases (Australia's Abatement Task And, 2013).

Governments around the world are now putting substantial effort into greenhouse gas emission reduction in order to slow the adverse effects of climate change. In Australia, more than 3.5 million people are living in premises with rooftop solar panels. The introduction of Electric Vehicles (EV) has been another promising step towards lower carbon emissions, but it will take some time until EV sales eclipse sales of oil dependent vehicles. The Australian Clean Energy Council estimated that the power produced from Australian rooftop solar panels will soon produce up to 3 GW which is equivalent to the electrical energy needed to run Melbourne's train network (Business Go Solar to Save Millions, 2014). According to the Australian Energy Market Commission EV sales will increase by 20% by 2020 and by 45% by 2030. The Commission also found that there will be an additional peak electricity demand of 1900 MW (Energy Market Arrangements For Electric And Natural Gas Vehicles, 2012).

Fig. 1 shows a traditional power grid where the power flow follows a hierarchical pattern and is functionally unidirectional. The power is generated from the power plant and supplied to the distribution domain via a high voltage electricity transmission network. In the distribution domain the power is transmitted to customers via substations and a low voltage distribution network. The advent of renewable energy and increasing use of various Distributed Energy Resources (DER) have made it necessary for the power grid to facilitate bidirectional power flows. To stabilize operational parameters and balance load profiles to enable bidirectional energy flow capability, the existing

* Corresponding author.
E-mail addresses: nazmusshaker.nafi@rmit.edu.au (N.S. Nafi), khandakar.ahmed@rmit.edu.au (K. Ahmed), mark.gregory@rmit.edu.au (M.A. Gregory), manoj.datta@rmit.edu.au (M. Datta).

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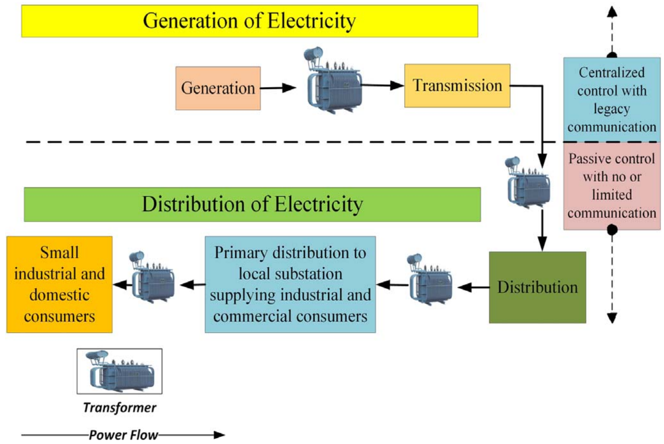

Fig. 1. Conventional power grid hierarchical placement of different domains.

power grid should be efficiently operated using enhanced control and monitoring technologies. The shift towards bidirectional energy flows and improved control and monitoring of the power grid has led to the evolution of the next generation power grid known as a SG and the technologies used to convert the existing power grid into a SG must be reliable, scalable, interoperable, secure and cost effective.

The SG concept has successfully grabbed the attention of the research community and research is now focused on how SGs can be used to address the limitations of the existing power grids. The operation of a SG should be flexible with increased control and monitoring that incorporates smart communications and remote interaction. For example SG substations should have the capability to coordinate their local devices autonomously (Fangxing et al., 2010).

Available survey journals (Gungor et al., 2013; Ye et al., 2013; Fang et al., 2012; Uslar et al., 2010; Rohjans et al., 2010) on SG cover a wide range of topics such as defining the SG communication network architecture, communication requirements, security issues and related standards. A study on cognitive radio networks (CRN) for SG is presented in (Khan et al., 2016) where several aspects of using CRN is discussed. Erol-Kantarci and Mouftah (2015) discussed the possibility to reduce operational costs by upgrading SG communication infrastructure to utilize energy efficient communication techniques. Applications such as demand response, distributed energy resources and grid monitoring are analyzed to identify energy efficient communication strategies. A comparison based analysis is presented in Kalalas et al. (2016) where several contemporary wireless standards have been reviewed. The study recommends Long Term Evaluation (LTE) as a key wireless solution to enable device-to-device communication in SG customer premises. Also, an application specific survey in (Deng et al., 2015) analyzed different mathematical approaches that are suitable for various types of demand response program modelling and another in (Rigas et al., 2015) highlighted various modelling approaches to implement artificial intelligent in EVs for SG applications. An elaborate study on the incorporation of SG applications can be found in (Bera et al., 2015). The breadth of the existing literature provides a vast range of SG challenges and this survey focuses on providing a guide to key issues and challenges for the research and engineering community. This review highlights the overall communication network architecture of SGs, major applications in different domains and communication requirements including power and standards. A range of communication models are presented with functionality explained to identify design considerations. Also, a comprehensive review of SG standards is presented to ensure the survey is comprehensive. This study provides a reference that is a starting point for a more detailed review of SGs, applications and architectures that map between the power grid and communication standards.

The paper is organized as follows. Section 2 presents a brief background on the transformation process of power grids to SGs and the potential benefits. Section 3 provides an overview on the SG architecture and communication network topologies. Section 4 discusses the existing SG standardization efforts. In Section 5 major SG applications and their communication requirements are presented. The conclusion and future research directions are presented in Section 6.

2. Background

According to the definition provided by the U.S. Department of Energy (DOE), SG is an energy supply network that supports bidirectional power flow, distributed and automated in nature, and permits real-time balancing of demand-supply via distributed and high speed computing and communications (The Smart Grid: An Introduction, 2010). However, the key differentiator, while converting the existing power grids to next generation SGs, will be designing robust SG compatible communication network infrastructure. Severe drawbacks are associated with the existing power grids (Gungor et al., 2013), such as: (1) disjointed architectural configuration; (2) bandwidth limitations for bidirectional communication; (3) inter-operability issues between vendor based network components; and (4) inefficient handling of huge data bursts generated from a large number of smart devices. Table 1 shows the key characteristics and major differences between conventional power grids and SGs.

According to Smart Grid Australia (Towards Australia's Energy Future: The Enabling Role of Smart Grids, 2012), next generation grids will introduce a number of major enhancements to conventional power grids including machine-to-machine (M2M) communications, real-time supply-demand management, asset supervision and improved operational efficiency (e.g. outage management). Research (Hamilton and Summy, 2011; Understanding the Benefits of the Smart Grid, 2010; Mallet et al., 2014) demonstrates various benefits of SGs and Hamilton and Summy (Hamilton and Summy, 2011) projected that in the USA investment of US$1 billion in SG technology may generate up to US$100 billion in Gross Domestic Product (GDP) growth. In the USA, it is predicted that the efficient power consumption behavior possible with a SG will add US$15–20 billion by 2020. As claimed in (Hamilton and Summy, 2011), SGs could be a potential economic development tool as demand grows for smart buildings and smart transportation systems creating more jobs for a skilled workforce. A study of European SG projects (Mallet et al., 2014) shows that most of the European countries are already at different stages of deploying smart meters. The study also shows that Italy and Sweden have fully installed smart meters while in Finland and Spain full phase deployment will be completed soon. The key reason for the mass roll-out of smart meters is real-time monitoring and reducing power consumption. The European Electricity Grid Initiative (EEGI) will generate 35% of electricity from the DERs by 2020 in preparation for planned green power production by 2050 (Mallet et al., 2014). To ensure a robust electricity supply network exists throughout the pan-European region the EEGI is seeking more customer participation and energy efficient schemes such as electric transportation. Generation, transmission and

Table 1
Conventional Grids vs. Smart Grids.

	Conventional Grid	*Smart Grid*
Power flow property	Unidirectional	Bidirectional
Generation profile	Centralized	Distributed
Grid configuration	Radial	Network
Integrating DERs	Very rare	Frequently
Sensor Devices	Few	Plenty
Monitoring	Restricted view	Self-monitoring
Control	Limited and passive	Pervasive and active
Outage recovery	Manual restoration	Self-reconfiguration

the distribution domain of power grids should have efficient communications and networking infrastructure in order to meet the complex requirements of SGs. Kwang-Cheng et al. (2010) mentioned that via communication infrastructure SGs would be able to gather detailed statistics about power generation, instantaneous or predicted consumption data, storage and distribution information. According to Cisco SGs are the combination of power grids and the communication networks that collect real-time data on power transmission, distribution and consumption (Internet protocol Architecture for the Smart Grid, 2010; Why IP is the Right Foundation for the Smart Grid, 2010). The two domains of the power grid where SG should impact the most are the transmission and distribution domains and there is a need for communication protocols designed to support data exchange between different network devices.

SG communication requirements vary significantly depending on the SG applications in use. Some of the SG applications are delay sensitive, where signals or other information should be delivered within a specific time period with guaranteed reliability, and SG applications may utilize a low data rate, for example a device, substation automation system or a Device Response Management (DRM) application. Also, applications may require high bandwidth with flexible delay bounds, such as Advance Metering Infrastructure (AMI), EV Charging and Vehicle to Grid (V2G) power transfer (Ye et al., 2013). Table 2 summarizes the bandwidth and latency requirements for several important SG applications. The next section focuses on the factors to determine the overall SG architecture as this is the first step towards designing the future SGs.

3. Smart grid communication network architecture

An understanding of the SG architecture provides a guide as to the requirements for SG communication networks. Different standardization bodies and organizations such as the DOE (The Smart Grid: An Introduction, 2010), the State of West Virginia (West Virginia Smart Grid Implementation Plan (WV SGIP), 2009) and the National Institute of Standards and Technology (NIST) (NIST Framework And Roadmap For Smart Grid Interoperability Standards, 2010) have developed conceptual SG architectures. However, the IEEE 2030–2011 standard has been broadly accepted as the first industry standard with a SG architecture, and configuration and inter-operability requirements (IEEE Guide for Smart Grid Interoperability of Energy Technology, 2011). Within the standard, an operational model called the Smart Grid and Interoperability Reference Model (SGIRM) is proposed in order to deal with the interoperability issues among different components of the communication network, power system and information technology platform. The SGIRM provides a guide to communication between SG generation, transmission, and distribution domains (Fang et al., 2012). An architecture model of the End-to-End (E2E) SG communications network based on the IEEE 2030 standard is shown in Fig. 2.

Modern SGs are structured in three layers called the Electric Power System Layer, Communication Layer and Application Layer. Interestingly, there could be numerous applications such as Automatic Meter Reading (AMR), AMI, Demand Response Management (DRM), Outage management, EV charging, Asset Management (AM), pilot protection (Nafi et al., 2014) and fraud detection developed and deployed via the Application Layer. Advanced intelligent modelling of the applications could resolve crucial interoperability issues. The Electric Power Layer comprises four domains including the generation domain, transmission domain, distribution domain and customer domain. A key challenge for SG in this layer is to provide two-way power flow between the different domains in order to balance energy demand and supply. The core of a SG exists in the Communication Layer and provides interconnections between all of the devices and corresponding systems.

At present, in the generation and transmission domain of the power system, legacy communications infrastructure is already in place to establish communications between the large substations. These substations are connected with the utility control center and third party networks mainly via a high bandwidth backbone network using Digital Subscriber Line (DSL), fiber, or cable. The distribution domain is typically a large geographical area that contains a large number of substations, feeder equipment, storage facilities, distribution assets and end-users. Wide Area Networks (WAN) connect the infrastructure with the control center. Additionally, 'last mile' connectivity is also provided to customer premises to support various applications within the home area network (HAN), building area network (BAN) and industrial area network (IAN). Hence, to enable a grid wide monitoring and control application, functionally the WAN remains a hub for the E2E SG network as it connects all of the domains of the Electric Power Layer. Fig. 3 shows the logical architecture of a WAN.

3.1. Neighborhood area network

The NAN connects customer premises to utility control centers via the AMI network. The main functional device of an AMI is the Smart Meter, which supplies consumption information and performs quality monitoring. It can also be used as an interface for energy control when used in the HAN and exchange information via the AMI system. The AMI system supports various types of intelligent SG applications such as Demand Response (DR), DERs, EV charging, and energy consumption in home displays. The network topology for a NAN is shown in Fig. 4 where all of the smart meters are connected to a Data Aggregation Point (DAP) that accumulates all the data received and transmits the data to a control center.

It's important to classify the required communication technology suitable for SG applications within NAN and WAN. According to (Gharavi and Bin, 2011), wireless communication may be the only practical solution to support last mile communications in the distribution domain, which provides connectivity from smart meters to the AMI access points. Hence, to implement wireless communication network technologies in SGs, the IEEE 802.15 Task Group 4 g (TG4g) was founded in December 2008 to define the Medium Access Control (MAC) and physical layer (PHY) protocols based on the IEEE 802.15.4 standard for wireless smart utility networks (SUNs) (IEEE Draft Standard for Information Technology, 2012). In this context it would be interesting to investigate the possible exploitation of TV White Space (TVWS) cognitive radio to enable M2M communication in

Table 2
Latency and bandwidth requirement for different SG applications (Gungor et al., 2013).

Application	*Bandwidth*	*Latency*	*Payload (bytes)*	*Reliability (%)*
Electric Vehicles (V2G, EV charging)	9.6–56 kbps	2 s to 5 min	255	> 98
Demand Response	14–100 kbps	500 ms–1 min	100	> 99.5
Meter reading	10–128 Kbps	2–15 s	200	> 98
Overhead Transmission Line Monitoring	9.6–56 kbps	15–200 ms	25	> 99.5
Substation Automation	9.6–56 kbps	15–200 ms	25	> 99.5
Outage management	56 kbps	2 s	25	> 98
Distribution automation Periodical	9.6–56 kbps	25–100 ms	150–200	> 99.5

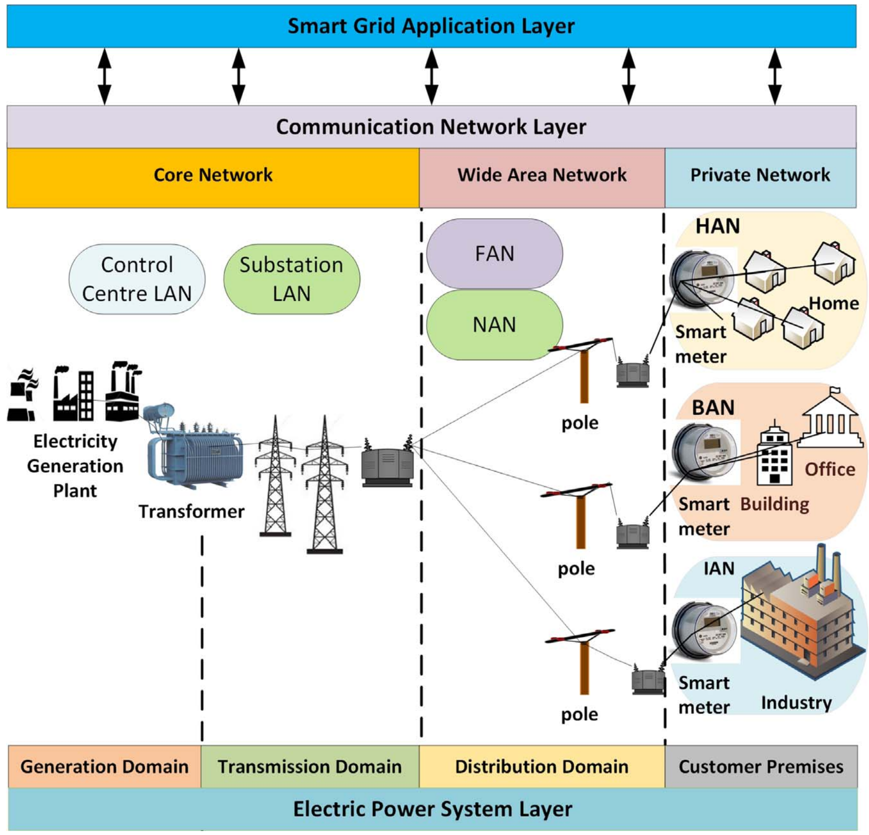

Fig. 2. Smart grid end-to-end network architecture.

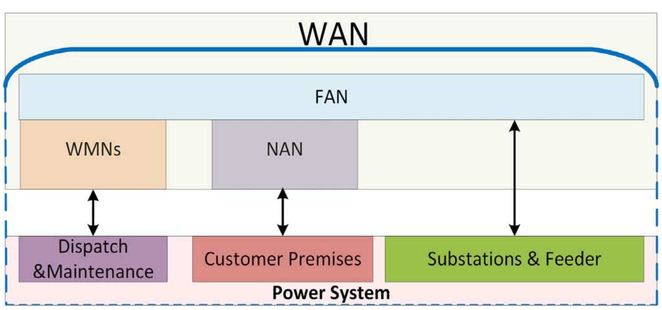

Fig. 3. Logical architecture of a SG wide area communications network.

the NAN domain. TVWS has been extensively studied (Cacciapuoti et al., 2015) specifically for SG applications and in general as a promising communication technology for smart meters. It can be a viable, although not yet fully standardized, solution for the SG ecosystem.

TG4g's key objectives is to provide a global standard to support large SG network applications. SUNs support large and geographically diverse networks with minimal infrastructure, potentially connecting millions of fixed endpoints.

3.2. Field area network

In a power system distribution domain high voltage electricity is converted to low voltage electricity via step down transformers in order to supply various users including commercial, industrial and home users. To perform various substation automation functions an adequate number of Remote Terminal Units (RTUs) along with Phasor Measurement Units (PMUs) and Intelligent Electronic Devices (IEDs) will be required throughout the SG distribution domain. In the SG distribution domain, the distribution feeders could be used as a point of common coupling (PCC) for the connected DERs and micro-grid components. Also, installing wireless sensors along with the feeder lines, poles and transmission towers would be required for developing distribution supervisory applications. Exchanging information between the distribution substations, feeder level equipment and applications would be the primary task of the Field Area Network (FAN).

The FAN is a communication network connecting the backhaul of a utility service provider to any specific service point of the distribution grid. Usually with a combination of various collectors, data concentrators and access points, a FAN provides the communication link between the substation segment and customer premises. Data collectors or sensors are connected to a centralized gateway via highly robust, reliable, low bandwidth FAN channels. At present the International Electromechanical Commission (IEC) 61850 standard is widely used for substation and distribution automation within the FAN and provides interoperability between IEDs and M2M communication. Based on the IEC 61850 protocol, the FAN latency requirements for mission critical data can vary between 3 and 10 ms (No-Gil et al., 2010).

3.3. Workforce mobile network

The Workforce Mobile Network (WMN) is used by the utility for maintenance purposes and to carry out daily operations. SG applications can be added to the WMN, for example V2G or G2V load management capable systems and smart vehicles with power that might be returned to the grid using location update services via tracking and navigation based on the Global Positioning System (GPS) (Wimax Applications For Utilities, 2008). Through the WAN, WMNs may access both the NAN and FAN to collect various types of information from equipment installed at customer premises. IEEE 802.11 s is devoted to the architecture and protocols of WMNs because

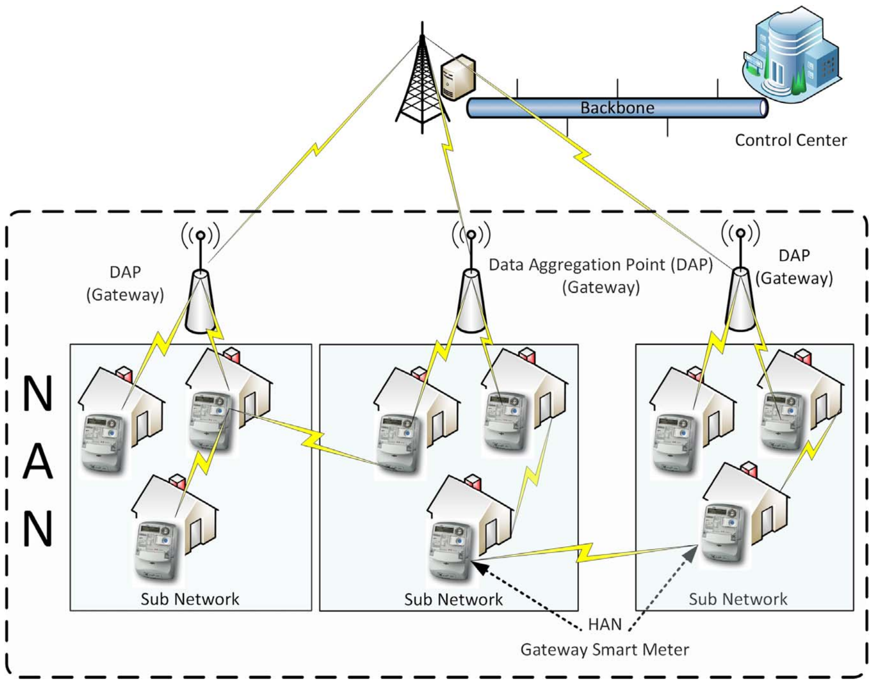

Fig. 4. NAN Network topology.

the communication requirement of WMN will be similar to non-M2M communication services including the Internet, voice or video applications (Ji-Sun et al., 2011).

4. Smart grid standardization

As a widely accepted SG standard, IEEE 2030 could be regarded as the key recent standardization effort. It defines the E2E smart grid architecture by integrating power systems with communications and information technology (IEEE Draft Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure, 2014). The IEEE P2030.1 and IEEE P2030.2 standards add to the detail provided in the IEEE P2030 standard. IEEE P2030.1 defines a knowledge based addressing terminology, mechanism, devices and planning requirements for EVs and ITS applications. IEEE P2030.2 covers discrete and hybrid energy storage systems integrated with the electric power infrastructure (Basso et al., 2012). Also, IEEE 1547 specifies the standards to interconnect distributed resources and renewable energy sources with the power grid. As a part of the SG.

standardization process, the IEEE has released several other standardized protocols. Fig. 5 shows the effort undertaken to map the SG protocol standards and Table 3 summarizes the SG standardization effort carried out by various organizations in different regions of the world.

The International Telecommunication Union Standardization Sector (ITU-T) has established a focus group called the Smart Grid Focus Group (SGFC) to develop recommendations, evaluate the impact of SG standards and strengthen the relationship between the ITU-T and power grid authorities. The International Standardization Organization (ISO) has put an effort in developing SG standards for home electronics architectures (defined by ISO/IEC 14543-3) (Ruta et al., 2011), and smart building design and control systems (defined by ISO 16484-5) (ISO, 2007). Also, Standards Australia (SA) has been commissioned by the Australian Department of Resources, Energy and Tourism in June 2011 to support SG in Australia (Australian Standards for Smart Grids- Standards Roadmap, Standards Australia (SA), 2012). There are a few other national and international standardization efforts by different agencies including the IEC, NIST, ANSI, CIGRE, ISO, and ESO specifying a wide range of SG attributes (Australian Standards for Smart Grids- Standards Roadmap, Standards Australia (SA), 2012).

The field of interest and application requirements identified in the approved IEEE standards are further classified as shown in Table 4.

To accommodate universal interoperability and standardize the general requirements for a SG architecture, the IEC formed the Smart Grid Strategic Group (SGSG) in 2008 (IEC Smart Grid Standardization Roadmap, 2010). So far more than 100 IEC standards, 44 recommendations, 12 application areas and general topics have been identified and examined by the IEC SGSG. As an initial SG implementation effort, within the distribution grid, a large number of legacy devices were successfully deployed utilizing systems based on IEC 61970 and IEC 61968 standards (Xuejian et al., 2010; Sucic et al., 2012).

For electrical substation automation, the IEC 61850 standard has been widely adopted in different parts of the world in recent years (Yong et al., 2011). SG security related issues are defined in the IEC 62351 standard (Yong et al., 2011). The standards play a vital role in the future transition of electrical distribution grids to SGs. To integrate communication technology along with the distribution system, the

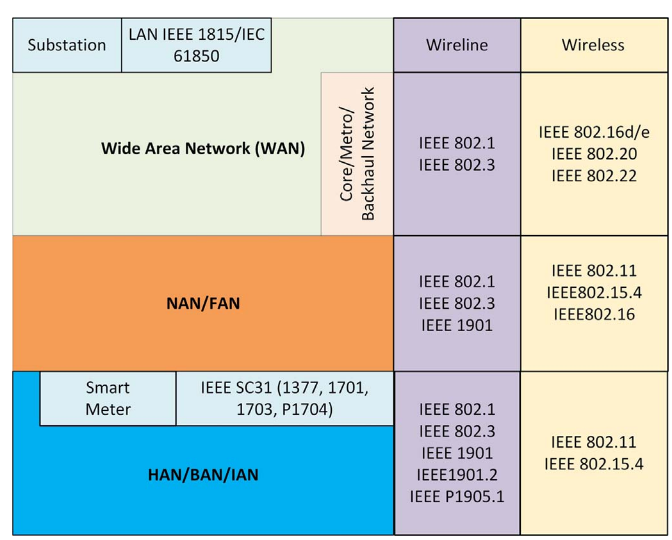

Fig. 5. Mapping of the IEEE standards with the SG architecture.

Table 3
SG standardization in different regions of the world.

Location	*SG standardization Organizations*
Australia	Standard Australia (Australian Standards For Smart Grids- Standards Roadmap, Standards Australia (SA), 2012)
United States of America	National Institute of Standards and Technology (NIST) (NIST Framework And Roadmap For Smart Grid Interoperability Standards, 2010)
	American National Standards Institute (ANSI) (Association, 2006)
European Countries	European Standardization Mandate M441
	Smart Meter Co-ordination Group ("Final Report Of The CEN/CENELEC/ETSI Joint Working Group On Standards For Smart Grids,", 2011)
	European Committee for Standardization (CEN)
	European Committee for Electro-technical Standardization (CENELEC)
	European Telecommunications Standards Institute (ETSI)
	Smart Grid Standardization Mandate M/490
	European Standardization Organizations (ESOs) (Standardization Mandate to European Standardization Organizations (ESOs) to Support European Smart Grid Deploymen, 2011)
Japan	Japanese Industrial Standards Committee (JISC) (Standardization Mandate to European Standardization Organizations (ESOs) to Support European Smart Grid Deploymen, 2011)
China	State Grid Corporation of China (Uslar et al., 2010)

standards can be considered as basic block to derive improved technology solutions. A summary of the IEC standards and their functional domain is shown in Table 5 (Uslar et al., 2010; Rohjans et al., 2010).

In the United States of America (U.S.A.) NIST (NIST Framework And Roadmap for Smart Grid Interoperability Standards, 2010) and ANSI (Association, 2006) participate in the standardization effort. The aim of the U.S.A. initiative is to provide SG standardization that focuses on interoperability, reliability, security and system maintenance. So far, NIST has identified 75 SG standards, developed a theoretical SG architecture model and identified priorities for additional standards including SG related cyber security and SG action plans (NIST Framework and Roadmap for Smart Grid Interoperability Standards, 2010).

SG would permit a large amount of raw data to be collected from the end users. It is quite clear that there are security and privacy threats on the user's personal data and behavior profile. The existence of SG could be jeopardized if the security and privacy issues are not carefully handled. A large monitoring and sensory device network would widen the horizon of possible intrusions and attacks. For example, an inefficient user authentication system may result in meter data manipulation. A possible protective measure to increase SG security and privacy could be achieved by increasing the capacity available to update network configuration and monitoring during operations. Software engineering approaches to handle SG security and privacy issues are discussed in (Salehie et al., 2012). Also, an agent based protective scheme is presented in (Ross et al., 2013) to handle different types of cyber-attacks on SG.

5. Smart grid applications and communication requirements

5.1. Advance metering infrastructure

To exchange information between the end users and the utilities AMI creates a two-way communication network comprised of advanced sensors, smart meters, monitoring systems, computer hardware, software, and data management systems. Within an AMI, smart meters are used to collect meter data or information on events via a periodic message exchange. AMI features and capabilities include a Meter Data Management System, Consumer Awareness systems, Interactive Services for Regulation of Energy Demand, systems to assist with avoidance of Electricity-related fraud and time accurate billing services (Benzi et al., 2011). There is a significant amount of literature available on AMI and AMR applications for SGs (Gungor et al., 2012; Paudyal et al., 2011; Sauter and Lobashov, 2011; Zaballos et al., 2011). Also, standards such as ANSI C12.19-2008 (American national standard for utility industry end device data tables, 2009), IEEE 1377 2012 (IEEE Standard for Utility Industry Metering Communication Protocol Application Layer (End Device Data Tables, 2012), and IEC 61968-9 (IEC, 2008) define and specify the technical requirements for the physical implementation of AMI applications and the IEC 61968-9 (Guangxian and Haitao, 2011) standard provides a more generic platform to cover various aspects of AMI based SG applications (e.g. meter connection status, meter data, outage management etc).

Fig. 6 shows a detailed architecture for AMI that includes the use of a data collection unit. Based on a RF/Zigbee communications network, Smart Meters act as an aggregator and send data to the data collection unit where a system controller transfers the aggregated data to the Meter Data Management System (MDMS). The MDMS processes incoming raw data to generate useful statistics and provides energy usage information for customers.

The basic component of an AMI system is the Smart Meter which sends meter readings in a scheduled manner to the MDMS. Meter reading data can be used for verification applications such as outage extent verification, outage restoration verification, billing applications and event based alarm applications such as meter health status (e.g. configuration and connection status), and voltage distortion (e.g. high or low).

An AMI has to deal with a large amount of data, as it collects information from all of the active meters within the network coverage. According to the Smart Grid Priority Action Plan 2 (PAP2) report, released by the U.S. NIST, meter density is 100, 800 and 2000 per square kilometer for rural, suburban and urban areas respectively (NIST Priority Action Plan 2 Guidelines for Assessing Wireless Standards for Smart Grid Applications, 2011). According to (Machine-to-Machine (M2M) communications study report, 2010) in an event of widespread power outage affected smart meters need to send an alarm to the control center within a few hundred milliseconds. It's highly challenging to send the 'last gasp' message within the delay boundary as all of the smart meters are bound to operate without battery power relying on capacitive charge only. Thus, for a large number of Smart Meters, providing network access within a short period of time is a crucial requirement of an AMR application (Machine-to-Machine (M2M) communications study report, 2010).

5.2. Demand response

DR is the mechanism used to reduce power generation peak demand through consumer participation and by optimally balancing or controlling their energy consumption or demand load. By optimally balancing energy consumption and power generation, either through adaptive pricing or by applying various load management techniques DR can offer efficient, reliable and cheaper power to consumers. Studies (Machine-to-Machine (M2M) communications study report, 2010; Cecati et al., 2011) explain various types of DR programs such as incentive-based programs (IBP) and priced based programs (PBP),

Table 4
Approved IEEE standards.

ield of Interest	*Approved standards*	*Field of Interest*	*Approved standards*
Interoperability	IEEE Std 2030-2014 (IEEE Draft Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure, 2014) IEEE Std 1377–2015 (IEEE Standard for a Convergent Digital Home Network for Heterogeneous Technologies Amendment 1: Support of New MAC/PHYs and Enhancements, 2015) IEEE Std 1701–2011 (IEEE Standard for Optical Port Communication Protocol to Complement the Utility Industry End Device Data Tables, 2011) IEEE Std 1702–2011 (IEEE Standard for Telephone Modem Communication Protocol to Complement the Utility Industry End Device Data Tables, 2011) IEEE Std 1703–2012 (Local Area Network-LAN/WAN) (IEEE Standard for Utility Industry Metering Communication Protocol Application Layer (End Device Data Tables, 2012)	***Networking and communications***	IEEE Std 802–2012 (IEEE Standard for Ethernet - Section 2, 2012) IEEE Std 802.1AB-2009 (IEEE Standard for Local and Metropolitan Area Networks– Station and Media Access Control Connectivity Discovery, 2009) IEEE Std 802.1AE-2006 (MAC) Security (IEEE Standard for Local and metropolitan area networksMedia Access Control (MAC) Security Amendment 2: Extended Packet Numbering, 2013) IEEE Std 802.1AR-2009 (IEEE Standard for Local and metropolitan area networks - Secure Device Identity, 2009) IEEE Std 802.1AXbk-2012 (IEEE Standard for Local and metropolitan area networks–Link Aggregation Amendment 1: Protocol Addressing, 2012)(Link Aggregation) IEEE Std 802.1Xbx-2014 (IEEE Standard for Local and metropolitan area networks – Port-Based Network Access Control Amendment 1: MAC Security Key Agreement Protocol (MKA) Extensions, 2014) (Port-Based Network Access Control) ISO 8802-2 IEEE 802.2 (Logical LinkControl) (IEEE Standard for Information Technology, 2013) IEEE Std 802.3bj-2014 (Ethernet) (IEEE Standard for Ethernet Amendment 2: Physical Layer Specifications and Management Parameters for 100 Gb/s Operation Over Backplanes and Copper Cables, 2014) P802.11-REVmb/D12 (PHY)(MAC) (IEEE Standard for Information technology–Telecommunications, 2012) IEEE Std 802.15.1-2005 (LAN to MAC info exchange) (MAC, PHY) (IEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks, 2005) IEEE Std 802.15.4m-2014 (MAC & PHY for LR WPANs) (IEEE Standard for Local and metropolitan area networks - Part 15.4, 2014) IEEE Std 802.15.4e-2012 (MAC for LR-WPANs) (IEEE Standard for Local and metropolitan area networks, 2012) IEEE Std 802.15.4g-2012 (PHY for LR-WPANs) (IEEE Standard for Local and metropolitan, 2012) IEEE Std 802.16-2012 (Air Interface for Broadband Wireless Access Systems) (IEEE Standard for Air Interface for Broadband Wireless Access Systems, 2012) IEEE Std 802.16n-2013 (Higher Reliability Networks) (IEEE Standard for Air Interface for Broadband Wireless Access Systems–Amendment 2, 2013) IEEE Std 802.16p-2012 (M2M application) (IEEE Standard for Air Interface for Broadband Wireless Access Systems–Amendment 1: Enhancements to Support Machine-to-Machine Applications, 2012) IEEE Std 802.16.1-2012 (WirelessMAN-Advanced) (IEEE Standard for WirelessMAN-Advanced Air Interface for Broadband Wireless Access Systems, 2012) IEEE Std 802.16.1a-2013 (Higher Reliability Networks) (IEEE Standard for WirelessMAN-Advanced Air Interface for Broadband Wireless Access Systems –Amendment 2: Higher Reliability Networks, 2013) IEEE Std 802.16.1b-2012 (IEEE Standard for WirelessMAN-Advanced Air Interface for Broadband Wireless Access Systems Amendment 1: Enhancements to Support Machine-to-Machine Applications, 2012) IEEE Std 802.20-2008 (Vehicular Mobility) (IEEE Standard for Local and Metropolitan Area Networks Part 20: Air Interface for Mobile Broadband Wireless Access Systems Supporting Vehicular Mobilityphysical and Media Access Control Layer Specification, 2008) IEEE Std 1901-2010 (Power Line Networks) (IEEE Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications, 2010)
Cyber Security	IEEE Std 1402-200 (Electric power substation physical and electronic security) (IEEE Guide for Electric Power Substation Physical and Electronic Security, 2000)	***Substation and Distribution automation***	IEEE Std 1379-2000 (Communication between RTUs & IEDs at substations) (IEEE Recommended Practice for Data Communications Between Remote Terminal Units and Intelligent Electronic Devices in a Substation, 2001)

(continued on next page)

Table 4 *(continued)*

ield of Interest	*Approved standards*	*Field of Interest*	*Approved standards*
	IEEE Std 1686 −2013 (Substation Intelligent Electronic Devices) (IEEE Standard for Intelligent Electronic Devices Cyber Security Capabilities, 2014) IEEE Std 1711-2010 (Cryptographic Protocol for cyber security of substation serial links) (IEEE Trial-Use Standard for a Cryptographic Protocol for Cyber Security of Substation Serial Links, 2011)		IEEE Std 1615-2007 (Network Communication in Substations) (IEEE Recommended Practice for Network Communication in Electric Power Substations, 2007) IEEE Std 1646-2004(IEEE Standard Communication Delivery Time Performance Requirements for Electric Power Substation Automation, 2005) (Time Performance Requirements for Electric Power Substation Automation) IEEE Std 1815-2012- Distributed Network Protocol (DNP3) (IEEE Standard for Electric Power Systems Communications-Distributed Network Protocol (DNP3), 2012) IEEE Std C37.94-2002 (IEEE Standard for N Times 64 Kilobit Per Second Optical Fiber Interfaces Between Teleprotection and Multiplexer Equipment, 2003) IEEE Standard for N Times 64 Kilobit Per Second Optical Fiber Interfaces Between Teleprotection and Multiplexer Equipment IEEE Std C37.111-2013 (IEEE/IEC Measuring relays and protection equipment Part 24: Common format for transient data exchange (COMTRADE) for power systems, 2013), Common Format for Transient Data Exchange (COMTRADE) IEEE Std C37.118.2-2011 (IEEE Standard for Synchrophasor Data Transfer for Power Systems, 2011) (Synchrophasor Data Transfer) IEEE Std C37.1-2007 (IEEE Standard for SCADA and Automation Systems, 2008) (SCADA and Automation Systems) IEEE Std C37.231-2006 (IEEE Recommended Practice for Microprocessor-Based Protection Equipment Firmware Control, 2007) (Microprocessor-Based Protection Equipment Firmware Control) IEEE Std C37.232-2007 (IEEE Recommended Practice for Naming Time Sequence Data Files, 2007) (Naming Time Sequence Data Files) IEEE Std C37.232-2011 (IEEE Standard for Common Format for Naming Time Sequence Data Files (COMNAME), 2011) (Naming Time Sequence Data Files (COMNAME) IEEE Std C37.236-2013 (IEEE Guide for Power System Protective Relay Applications Over Digital Communication Channels, 2013) (Protective Relay Applications over Digital Communication Channels) IEEE Std C37.238-2011 (IEEE Standard Profile for Use of IEEE 1588 Precision Time Protocol in Power System Applications, 2011) (Use of IEEE Std 1588 Precision Time Protocol in Power System Applications) IEEE Std C37.239-2010 (IEEE Standard for Common Format for Event Data Exchange (COMFEDE) for Power Systems, 2010) (Event Data Exchange (COMFEDE) IEEE Std C37.244-2013 (IEEE Standard for Common Format for Event Data Exchange (COMFEDE) for Power Systems, 2010) IEEE Draft Guide for Phasor Data Concentrator Requirements for Power System Protection, Control, and Monitoring
Electric power infrastructure	IEEE P2030.100 (IEEE Draft Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure, 2015)	***Renewables***	IEEE Std 1547.3-2007 (IEEE Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems, 2007) IEEE Guide For Monitoring, Information Exchange, and Control of Distributed Resources Interconnected With Electric Power Systems
AMI	IEEE Std 1377-2012, Utility Industry Metering Communication Protocol Application Layer Standard (End Device Data Tables) (IEEE Standard for Utility Industry Metering Communication Protocol Application Layer (End Device Data Tables, 2012)	***Device data tables***	IEEE P1703 (IEEE Draft Standard for Local Area Network/ Wide Area Network (LAN/WAN), 2012) Draft Standard for Utility Industry End Device Communications Module
Power quality and energy efficiency	IEEE Std 1159.3-2003 (IEEE Recommended Practice for the Transfer of Power Quality Data, 2004) IEEE Recommended Practice for the Transfer of Power Quality Data	***EVs***	IEEE Std 1901-2010 (IEEE Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications, 2010) IEEE Std 1901.2-2013 (IEEE Standard for Low-Frequency (less than 500 kHz) Narrowband Power Line Communications for Smart Grid Applications, 2013)

Table 5
SG standardization in different regions of the world.

Standard	*Point of Interest*
IEC 61970/61968	Common Information Model (CIM) (IEC, 2007, 2008)
IEC 61850	Substation Automation Systems (SAS) and DER (IEC, 2003)
IEC 62351	Security for the Smart Grid (I. Std., 2006)
IEC 62357	TC 57 Seamless Integration Architecture (Std, 2009)
IEC 60870	Communication and Transport Protocols (Std, 2003a, 2003b, 2006)
IEC 61400-25	Communication and Monitoring for Wind Power Plants (Std, 2006)
IEC 61334	DLMS (Std, 1996)
IEC 62056	COSEM (Std, 2006)
IEC 62325	Market Communications using CIM (Std, 2004)

real-time pricing (RTP), time of use (ToU) rate, critical peak pricing (CPP), extreme day pricing (EDP) and extreme day CPP (ED-CPP). In DR programs, end users take part in the energy business by changing their energy consumption behavior with respect to variable energy price units rather than fixed price units which results in profits by both the utilities and customers (Cecati et al., 2011). There are various types of demand response based on implementation and long term or short term outcomes. A brief summary of the available DR programs are shown below.

5.2.1. Time of use

ToU is a DR program where billing months are segmented into hourly windows that are assigned a different price based on production cost. A price signal is provided to consumers to minimize energy usage during peak periods. For example, ToU could include daily peak and off peak pricing. Variable pricing could be extended to differentiate between weekdays and weekends. Also, seasonal pricing could be incorporated in the ToU for implementing DR programs.

5.2.2. Critical peak pricing

CPP is an optional scheme that is often combined with on peak and off peak ToU periods and may not be applied during specific periods. CPP will be in operation only when the Load Serving Entity is serving a load demand that is deemed to be critical. Critical state could include reaching maximum capacity, and there could be multiple CPP events on a single day.

5.2.3. Peak time rebate (PTR)

In this kind of DR program a customer can be paid for not using the electricity during the CPP hours. A notice before initiating the event or during the event would be sent to the customers participating in the DR program. The total demand load reduced by the customer during CPP hours is measured by comparing with the basic demand load of same hours in a normal day. Based on the amount of demand reduction a rebate could be claimed by the customer.

5.2.4. Real time pricing (RTP)

In a RTP DR program, customers are provided with day ahead or hour ahead pricing of energy units. The energy price units determine energy usage limits where the customers volunteer to minimize energy consumption in order to maximize their saving. Participants of this program are usually charged for exceeding the assigned Customer Baseline (CBL) load curve. Also, customers receive reward in term of credit if the usage remain below the CBL.

5.2.5. Direct load control (DLC)

When DLC becomes unavoidable it is necessary to initiate load reduction, such as load shedding in order to maintain system reliability and cope with high production costs. DLC provides credits to participants for reducing load during these events. There are two types of load reduction mechanism: (1) the DLC program maintains direct control over consumer loads that may be shed, and (2) participants maintain control over loads that may be shed. If a participant does not shed a load that is part of a DLC program penalties may apply.

5.2.6. Remote load control (RLC)

This is more advanced DR program where household appliances are remotely controlled using an advanced algorithm to reduce demand load. A M2M communication infrastructure is used and price signals

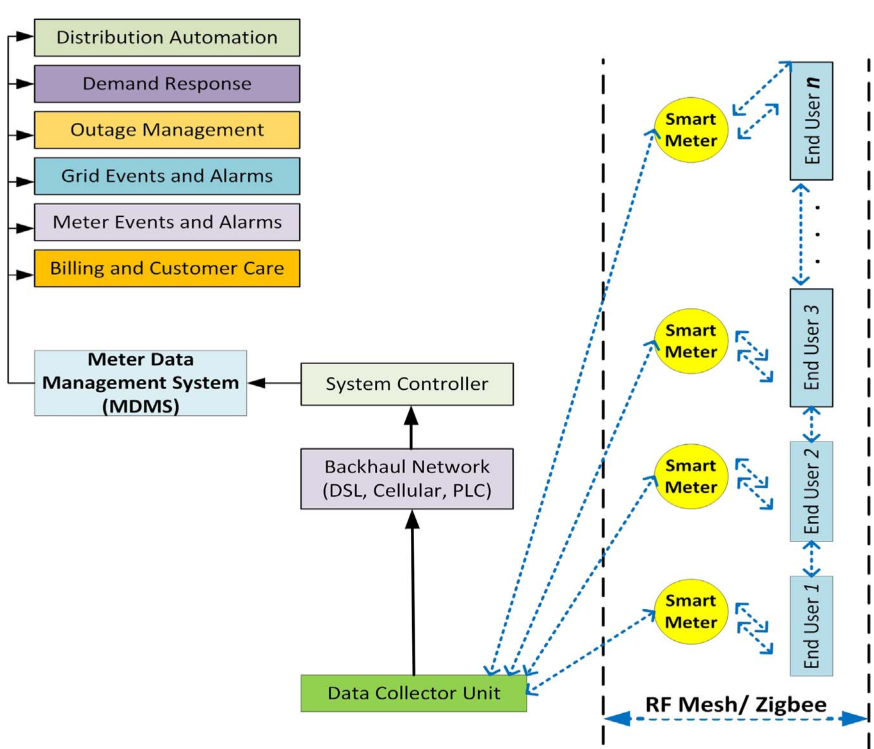

Fig. 6. Logical representation of SG automatic metering infrastructure.

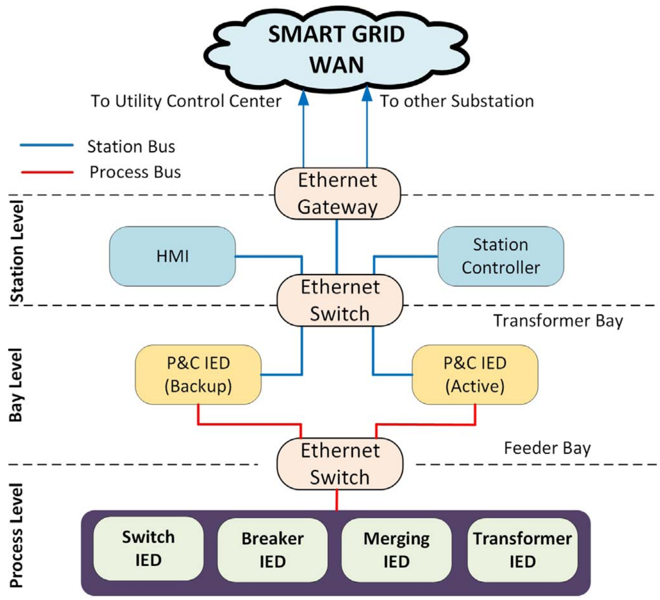

Fig. 7. Intra Substation communication network.

are sent to the automated electrical home appliances so that time of operation can be scheduled based on the energy unit price. There are three types of loads defined for RLC:

5.2.6.1. Interruptible loads. This load can accept an interruption and have its operation shifted to other time to avoid a peak period. Electrical appliances, like water pumps, dish washers, and dryers, can be shifted to a different time slot to avoid peak periods. A load control command is required to initiate the interruption and the operation time shift.

5.2.6.2. Reducible load. A reducible load indicates that operations can be reduced for a specific amount of time. For instance, an air conditioner can reduce its energy consumption and maintain a minimum threshold of comfort level during a peak time if the temperature is set to high for that period. Hence, periodic interactions are required from the distant DR server at the time of load management.

5.2.6.3. Interruptible load. Iinterruptible loads can be shed over a peak period based on the run time cycle length. For example, if the run time cycle is 60 min, then 50% reduction will result in a 30-min cycle during a peak hour. Two control signals are required to initiate and complete the cycle limit.

There are factors that affect DR program operations including regulations, energy pricing, environmental requirements and control signal communications. For example, during summer the wholesale electricity price may increase as there will be more demand for air conditioning. In this case, there is likely to be multiple RLC sessions initiated by the DR controller. Hence, this will result in a high SG communication traffic load and a robust communication network will be essential. Additionally, in the case of price based DR programs, remote servers utilize multicast signaling to the subscribed customers. Usually, transmission of these traffic loads are delay tolerant but at the same time they are very sensitive to packet loss. However, according to (Communications Requirements of Smart Grid Technologies, 2010) DRM programs require bandwidth of 14–100 Kbps per device to provide system continuity and to remotely control smart appliances for peak demand management.

The communication loads vary with the type of DR program being used. DR programs based on price have relatively lower communication traffic load compared to the other RLC programs as they require increased information exchange. Among the RLC programs, the Interruptible Load program require a lower traffic load because it involves fewer control signals to interrupt and reschedule operations. On the other hand, a Partially Interruptible Load and Reducible Load programs require higher communication traffic as more control signals are exchanged.

5.3. Substation automation

In SGs, substation automation via M2M communication facilitates advance monitoring, protection and control functions for the transmission and distribution substations (e.g. protection signals to relays) and feeder equipment (e.g. automatic re-closers and switches for fault isolation). Widely adopted standards for this part of the power grid are the IEC 61850 and Distributed Network Protocol: version 3 (DNP3) or IEEE 1815 standards. The IEC 61850 standard is fairly comprehensive when it comes to defining substation automation features, including control applications and real time high-bandwidth protection. According to the IEC 61850 standard, communication between interoperable IEDs will be based on the Internet Protocol (IP) and Ethernet standards. Additionally, to differentiate various traffic flows, five types of priority based communication services are defined:

I. Abstract Communication Service Interface (ACSI)
II. Generic Object Oriented Substation Event (GOOSE)
III. Generic Substation Status Event (GSSE)
IV. Sampled Measured Value (SMV)
V. Time Synchronization (TS)

5.3.1. Intra-substation communications

The IEC 61850 standard covers control and communication with substation equipment and devices. Fig. 7 shows the communication architecture of intra-substation communication which has three classified levels known as station level, bay level and process level. The switch yards' equipment including current transformers (CT), potential transformers (PT), input output (I/O) devices, sensors, actuators, circuit breakers, switches, and merging unit (MU) IEDs are part of the process level.

Analogue voltage and current values are collected from the field CT and PTs via the MU IEDs and sent to the protection and control (P & C) IEDs at the bay level. The station level comprises the station controllers and human device interfaces (HMI). Two separate Ethernet subnetworks that are called the process bus and substation bus are defined in the IEC 61850 to facilitate QoS implementations. The process bus handles delay sensitive communication between P & C IEDs and switch IEDs, breaker IEDs as well as the merging IEDs. Communication between different bays and station controllers is handled by the station bus. However, communication with external networks, including other substations and the utility control center occurs via a gateway to the substation.

5.3.2. Inter-substation communications

Inter-substation communication or M2M communication between different IEDs in a distribution domain requires application data transmission from telemetry or sensors to an aggregator. M2M communication is based on reliable delivery of single message within a strict delay boundary. Also, the extensive use of microprocessor-based protective relaying techniques enables development of wide area monitoring, protection and control (WAMPC) system (Terzija et al., 2011), a converging process towards a universal SG communications network (Application of Peer-to-Peer Communication for Protective Relaying, 2002; Schweitzer et al., 2001; Hunt et al., 2008) solution.

According to IEC 61850, the type of message in the inter-substation communication is defined by the GOOSE profile. The GOOSE message can be exchanged using IP and can also support both unicast and multicast. Thus, the shift to IP based integrated SG communications networks for advanced protection and control schemes in the power transmission and distribution grid could be an important feature of the inter-substation communication. However, performance of an M2M application is evaluated in objective terms such as measurement of delay or packet arrival rate while using any wireless communication system. So, to accommodate different types of SG traffic along with the protection traffic, a wireless communication solution must be efficient and ensure high E2E transmission reliability.

A number of proposals can be found in the literature on using digital communications to develop protective applications at the SG distribution domain (Application of Peer-to-Peer Communication for Protective Relaying, 2002; Schweitzer et al., 2001; Hunt et al., 2008). IEEE Draft Standard for Local Area Network/Wide Area Network (LAN/WAN) (2012) presents a report released by the IEEE Power System Relaying Committee (PSRC) on protective relaying applications using the forthcoming SG communications infrastructure. Clement-Nyns et al. describe the use of wireless communication media such as microwave, narrow band radio, and spread spectrum radio for pilot protection schemes (Apostolov, 2012). Other pilot protection applications based on the IEC 61850-based GOOSE messaging are described in (Sanders, 2010; Khan et al., 2013). WiMax and Zigbee based pilot protection schemes for smart distribution domain are proposed in (Khan et al., 2013; Smit, 2012).

Among the common protection methods, directional comparison blocking (DCB) and permissive over-reaching transfer trip (POTT) (Maciejowski, 2001) are well cited in the literature as popular pilot protection schemes. The key development challenge for protection scheme communications is to transfer the GOOSE packets with the pilot trip/block signals within a specified time delay in order to isolate the fault otherwise the relay would trip automatically. Also, the signal should be transferred as fast as possible because the associated switch/circuit breakers will be delayed by the data communication time plus a small guard time (Mirchandani and Head, 2001). So, to maximize the efficiency of the protection scheme the communication delay should be minimized as much as possible. Usually, POTT operating delay is 30–35 ms whereas the DCB operating delay is 80 ms (including relay operation time) for a 50 Hz power system. Hence, Maciejowski (Maciejowski, 2001) suggested that with a 5 ms delay for high speed relay operation a pilot signal would have a delay budget of 25–30 ms for the communications network. Table 6 summarizes the communication requirements and service types of substation automation.

5.4. Distributed energy resources

Distributed Energy Resources (DER) have significantly increased due to the growing trend towards rooftop solar panels and other renewable energy resources, including wind power. Renewable energy resources are advantageous because of lower carbon emissions and due to lower installation costs the DER are becoming more popular. However, some of the renewable energy sources require energy storage devices for low generation periods.

The additional controllable power provided by energy storage devices could be used to provide consistent supply with more reliability and capacity. However, the bandwidth requirement for extracting instantaneous information from the generation points is about 9.6–56 Kbps. The latency range can vary from 300 ms to 2 s while the reliability must be within 99–99.99% (Communications Requirements of Smart Grid Technologies, 2010).

Required power to drive an EV ranges from 10 to 200 kW and this power is usually supplied from batteries or fuel cells. By V2G operation the stored energy can be sent back to the grid, if needed. So, EVs may work like a mobile DER and the stored power of the batteries or generated power from the vehicle's kinetic energy can be supplied to the power grid. Hence by using EVs as a power source it would be possible to increase power generation during peak times, improve back-up capacity and power system reliability. Additionally, renewable energy sources can be integrated with the V2G, the vehicle can provide sufficient back-up for renewable energy generation and act as storage device. The communication requirement of V2G application depends on the speed of the vehicle. The authors of (Clement-Nyns et al., 2010) provide the communication requirements for parked fleet of vehicles. Wireless communication technologies like ZigBee or Wi-Fi will support V2G applications in parking areas. For moving vehicles, mobile cellular communication is appropriate. Power transmission enhancement is an important factor for planning large scale power systems and regional transmission because the EVs introduce new types of loads to the grid. The communication bandwidth requirement for a V2G application is 5–10 kbps and the latency requirement is up to 2 s (Communications Requirements of Smart Grid Technologies, 2010).

5.5. Wide area measurement

In a Wide Area Measurement System (WAMS) the power grid status is continuously monitored and a Phase Measurement Unit (PMU) is used to update system state informatics and real-time power quality measures. To get accurate real-time measurements, GPS data can be used to allocate a time stamp with each measurement (Phadke, 2008). High resolution phase information can be obtained by the utility with precise measurement synchronization and the utility could initiate an appropriate response within the delay bound to protect the WAN from a black-out (Xuejian et al., 2010). In the existing power grid PMUs are installed within the generation and transmission domain of the power grid taking into account the unidirectional power flow from generation to distribution. However, in order to enable bidirectional power flow and real-time system monitoring, PMUs need to be deployed at SG distribution points (Wache and Murray, 2011). Fig. 8 shows the WAMS network topology.

To build a WAMS it is essential to deploy PMUs within the regional and national power grids and usually a Phasor Data Collector (PDC) collects all of the measurements from a network where the PMUs are deployed. The PDC aggregates and transmits the data to the Central Control (CCN) location via the transit and backhaul networks.

The IEEE C37.118.2–2011 provides the PMU data communication specifications. The reporting frequency is the key factor used to determine the communication load which may vary between 10, 25 Hz and 10, 12, 15, 20, 30 Hz for a 50 Hz and 60 Hz based power systems respectively. However, the main communication requirement for WAMS applications is to establish a secure and reliable communication link between PMUs and PDC within the specific latency.

6. Conclusion

To present a comprehensive survey on smart grid architecture, potential applications and standardization effort, this paper reviews recent literature, reference models and standards. As SGs are an enormously broad and diverse network of electronics devices there is

Table 6
SG Communication specification for substation automation.

Msg. Type	*Application*	*Service type*	*Time boundary (ms)*
A1	Fast Message (Trip)	GOOSE, GSSE	3–100
A2	Fast Message (Other)		20–100
B	Medium Speed	ACSI	100
C	Low Speed		500
D	Raw Data	SMV	3–10
E	File Transfer	ACSI	> 1000
F	Time Synchronization	TS	(Accuracy)

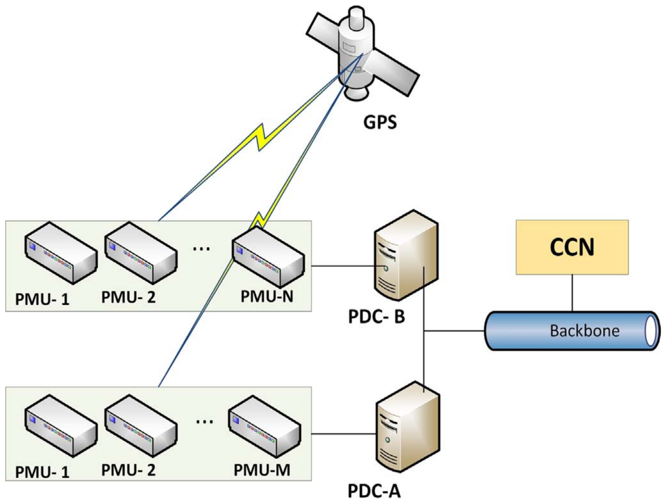

Fig. 8. Network topology of a Wide Area Measurement System.

a challenge to model the communication network requirements. A summary of the standardization effort is provided for future investigators, professionals and researchers.

This paper initially focuses on the SG communication network architecture, network topologies and functions. The standardization initiative taken by different organizations, nations and regions are then described. Finally, potential SG applications and communication requirements are presented. This paper aims to provide information about how to build a smart, reliable, secure power grid and to identify the requirements and challenges associated in the development of SG applications. Future research into the potential for a software defined networking (SDN) paradigm for SG M2M communication provides a logical extension of SDN implementations in broadband networks. Very limited studies have been identified in the literature on SDN based SG systems (Cahn et al., 2013; Dorsch et al., 2014; Goodney et al., 2013) making this an interesting and challenging topic for further research.

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Nazmus Shaker Nafi (S'14) received the B.Eng. (Hons.) degree in Communication from the International Islamic University Malaysia (IIUM), in 2010, and the M.Phil. degree in Computer engineering from the University of Newcastle, Newcastle, NSW, Australia, in 2013. Currently, he is a Ph.D. candidate in the RMIT University, Melbourne, Australia. His current research interests include Smart Grid communication systems, wireless network architecture, Machine to Machine, Software Defined Networks and Internet of Things.

Khandakar Ahmed (M'11) is a Lecturer at School of IT & Engineering, Melbourne Institute of Technology, Melbourne, Australia and currently an affiliated researcher, Australia-India Research Centre for Automation Software Engineering (AICAUSE), RMIT University, Melbourne, Australia. He received his Ph.D. from RMIT University, Melbourne, Australia in December, 2014, M.Sc. in Networking and e-Business Centred Computing (NeBCC) from the consortia of University of Reading, UK; Aristotle University of Thessaloniki, Greece; and University of Charles III de Madrid, Spain. Dr. Ahmed has authored or co-authored more than 30 publications in the form of journal Article, peer reviewed conference proceedings, book chapter and book. He has also worked as the reviewer for many Journals including Parallel and Distributed Computing (JPDC), Journal of Computer Networks (ComNet) and Journal of Ad-hoc Networks. His research interest includes Software Defined Wide Area Network, Software Defined Wireless Network, Wireless Sensor Network, Smart-Grid and Cloud Networks.

Mark A Gregory (SM'99) is a Fellow of the Institute of Engineers Australia and a Senior Member of the IEEE. Mark A Gregory received a Ph.D. from RMIT University, Melbourne, Australia in 2008, where he is a Senior Lecturer in the School of Engineering. In 2009, he received an Australian Learning and Teaching Council Citation for an outstanding contribution to teaching and learning. He is the Managing Editor of two international journals (AJTDE and IJICTA) and the General Co-Chair of ITNAC. Research interests include telecommunications, network design and technical risk.

Manoj Datta (S'06, M'11) received the B.Sc. degree (first class with honours) in Electrical and Electronic Engineering from KUET, Bangladesh in 2003 and M. Eng. and D. Eng. degrees in Electrical and Electronics Engineering from University of the Ryukyus, Japan, in 2008 and 2011 respectively. From 2003 to 2011, he was an Assistant Professor in the Department of Electrical and Electronic Engineering, KUET, Bangladesh. From April 2011 to February 2012, he was a JSPS Post-Doctoral Research Fellow in the Faculty of Engineering, University of the Ryukyus, Japan. From 2012 to 2013, he was an Assistant Professor in the Department of Human and Information Systems, Gifu University, Japan. Since June 2013, he has been with the School of Engineering, RMIT University, Melbourne, Australia, where he is a Lecturer. Dr. Datta was the recipient of the University of the Ryukyus President's honorary award for outstanding Ph.D. thesis. He is a member of the Institute of Electrical Engineers, Japan. His research interests include micro-grid modelling, grid integration of DGs, and intelligent ancillary services in smart grids.