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Information and Communication Technologies in Modern Electrical Networks: A Brief Review

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Abstract- Information and communication have a long history in power systems. The advancement of digital signal processing, digital circuits and RF circuit manufacturing provide a solid foundation for new generations of digital grids with wide monitoring and controlling capabilities. Information and communication build the cornerstone for a reliable, secure, and efficient network operation. In this paper, relevant information and communication technologies in modern power systems are covered and classified according to the application areas, communication protocols and network areas. Moreover, applications based on information and communication technologies were briefly discussed.

Keywords Smart grids, information and communication in power systems, wireless communication, distributed renewable energy resources, applications of smart grids, challenges of smart grids.

1. Introduction

According to a study conducted by the International Energy Agency (IEA), the generation of electricity and heat contributed to 44% of the CO2-emissions globally [1]. The pace towards CO2-neutrality is moving fast to decarbonize the energy sector and other sectors. New technologies and innovations are being deployed to enable decarbonization as well as digitalization resulting in formation of the next generation grids, also known as Smart Grids (SG). The term smart grid does not have a specific definition. IEEE defines a SG as a revolutionary undertaking-entailing new communications-and-control capability, energy sources, generation models and adherence to cross-jurisdictional regulatory structures [2] while IEA defines it as an electricity network system that uses digital technology to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users [3]. Information and Communication Technology (ICT) is one of the important enablers of the smart grid technologies.

Due to the growing penetration of Distributed Renewable Energies (DRE), old concepts and aging infrastructure will no longer be valid for the future. In aging power grids, the power flows from central power plants through transmission lines to the utility companies and finally to the end-consumer. In this structure, the power flow can be controlled relatively easy. On the other hand, in SGs power is produced by DRE and consumed locally by the end-customer. ICT allows the network operator to communicate with the DRE to balance the generation and consumption as well as to keep the power quality in the permissible ranges.

Additionally, ICT allows new features such as system reconfiguration, fault detection and self-healing using Fault Location and Service Restoration (FLISR), increase the controllability and monitorability of the grids using Supervisory Control and Data Acquisition (SCADA) and Energy Management Systems (EMS). These new features can help improving the power and service quality and will be discussed separately in Chapter 4. Table 1 shows the differences between traditional grids and smart grids.

Table 1. Comparison between smart grids and traditional power grids

	Traditional Grid	**Smart Grid**
Power flow	Unidirectional	Bidirectional
Power generation	Centralized	Decentralized
Communication	One-way	Two-way
Technology	Analog/ Electromechanical	Digital
Structure	Radial	Mesh
Service Restoration	Manual	Self-healing
Reconfigurability	Not possible	Self-reconfigurable
Controllability and monitorability†	Low	High
Complexity*	Low	High

† In comparison with smart grids.

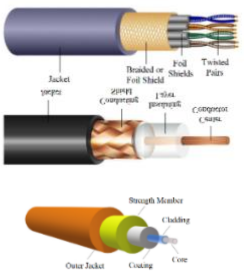
2. Information and Communication Technologies in Power Systems

ICT is highly considered as the building block for a secure, safe, stable, and economic grid operation. Together with sensing and metering technologies, ICT allows a high degree of monitoring and controlling of power system processes and equipment. In power systems ICT has a long history in the power transmission grids. Almost all substations are monitored and controlled online by EMS. On the other hand, less than 10% of transformer substations and Ring-Main Units (RMU) are monitored and controlled in distribution networks [4].

In general, there are two types of communication technologies used in power systems, either wired or wireless communication. Wired and wireless communication networks have different hardware requirements, coverage ranges, reliability, and different costs. The following section handles different ICT in power systems and their properties.

2.1. Communication Cables

Communication cables are used to establish communication channels between two ends (sending and receiving ends), which are physically connected using cables. It is used since 1850 when Samuel Morse sent his first telegraph message through the transatlantic cable [5]. Since then, wired communication technologies have been developing. Modern communication cables use optic fibre to transmit digital data, including telephone, internet, and personal data. Other communication cables are also used in power systems such as coaxial cables and twisted-pair cables. The type of cable is selected depending on the application and its requirements. Fig. 1 shows the structure of different communication cables used in power systems.



Twisted Pair Cable

Coaxial Cable

Optic Fiber Cable

Fig. 1. Structure of different communication cables [6].

Data and information can be transferred through cables in form of electrical signals (in coaxial and twisted-pair cables) or light signals (in optic fibre cables). The speed of the signal inside the cable normally depends on the sending end. However, each communication cable technology has a maximum limit for transferring data (see Table 2). The bandwidth of a cable defines the frequency of how often signals can get sent per unit time, depending on the application, e.g., critical applications such as SCADA and EMS as well as FLISR. External factors such as magnetic or electric fields, neighbouring communication cables, vibrations, etc. can cause signal interference and noise resulting in loss of the data transmission quality.

A very common connector type in the power systems is the Ethernet cables using TCP/ IP protocols. Ethernet was mainly used as a network solution for office and business applications; however, its high-speed characteristics make it an interesting communication technology for substations [7]. While Ethernet connections used for office and business communication have twisted-pair cables as a transmission medium, Ethernet connectors in substations use optic fibres. The reasons for that are its ability to transfer large amount of data with high speeds and the resistance to signal interference. Table 2 shows an overview and criteria of different communication cables.

Table 2. Characteristics of different communication cables [8]

	Twisted pair cables	Coaxial cables	Optical fiber cables
Speed	Up to 10 Gbps	Up to 10 Mbps	Up to 200 Gbps
Bandwidth	Up to 500 MHz	Up to 0.75 GHz	Up to 4.7 GHz
Distance‡	Up to 100 m	Up to 500 m	Up to 80 km
Attenuation	High	Medium	Low
Signal Interference	High	Low	Very Low

The wired communication technologies mentioned are optimal and cheaper when connecting communication points within small distances (E.g., connecting field devices with the control room within a substation). Establishing communication between substations (SS) and control centres (CC) that are hundreds of kilometres apart will be costly and ineffective. Legacy transmission systems use Power Line Communication (PLC), a communication mean which is used to transfer data between two points separated by long distances. PLC is implemented by adding a modulated carrier signal to the power wires or power cables [9]. Data rates can reach several Mbps. It is mainly used in the transmission system as a default communication technology. Data is transmitted with low frequencies, typically in kHz-range (kilohertz). However, power cables are designed to carry currents with 50 Hz or 60 Hz frequency and transmission of signals with kHz frequencies will cause propagation and power quality problems. Additionally, the communication between two substations is interrupted when the disconnectors are open, i.e., this is the time when the communication is needed [10].

Today's transmission systems use composite overhead conductors, also known as Optical Ground Wire (OPGW), to transmit information over long distances. The OPGW incorporates an inner core of optical fibre tubes to transfer data and an outer layer of Aluminium and steel conductor strands (see Fig. 2) to shield the line from lightning strikes. It allows high speed and secure data transmission.

‡ Distance without amplifier.

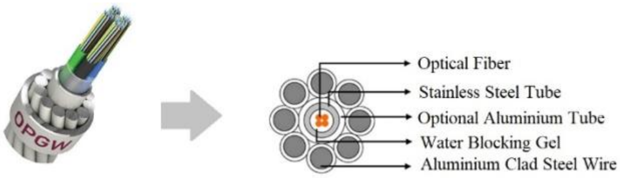


Fig. 2. Structure of OPGW [11, 12].

2.2. Wireless Communication

Wireless communication establishes communication channels between two or more ends, which are not physically connected. It uses radio frequency (RF), infrared, Bluetooth, microwaves, etc. Data and information can be transferred in form of electromagnetic waves which takes the air as a communication medium. Today wireless communication is a popular and cheap mean to transfer data between two or more ends due to the absence of cables.

Unlike wired communication, wireless communication has many different technologies. Since the 2000s wireless communication has rapidly developed due to the advancement of digital signal processing, digital circuit, and RF circuit manufacturing [13]. Table 3 shows the relevant wireless technologies in power systems and their properties.

Table 3. Relevant wireless communication technologies for power systems [9]

	Satellite	Cellular Networks	ZigBee	WiMAX
Speed	1000 Gbps	Up to 100 Mbps	20 – 250 kbps	70 Mbps
Bandwidth	1.83 – 3 GHz	2.1 GHz	868 MHz – 2.4 GHz	1.1 – 2 GHz
Range	100 – 6000 km	12 – 49 km	10 – 100 m	100 m – 50 km
Attenuation	Low	High	Medium	Medium
Signal Interference	Low	Medium	High	Low

Satellite: is used as a mean of communication in power systems to provide real time data in rural areas without cellular coverage. Its applications are in FLISR, frequency management as well as control and monitoring of remotely located substations.

Cellular Networks: are widely spread and commonly used for commercial applications, such as communication by mobile phones. They can be also used to transfer power data with high rates up to 100 Mbps. Cellular networks have the advantages that the infrastructure and security algorithms exist already. Only the service provider costs are applicable. In [14], 5G technology was identified as a key enabler of highly distributed network in the Finnish grid. It allows wide use of cellular networks, including critical applications such as protection and Distribution Automation (DA).

ZigBee: is a communication technology based on the IEEE 802.15 standard. Its uses are mainly focused on applications that require low data rates, short ranges, and low energy demands. It allows connection of up to 60,000 devices [9]. According to [15], ZigBee is integrated as a communication protocol in more than 35 million smart meters around the world.

WiMAX: is a communication technology based on the IEEE 802.16 standard. WiMAX operates similar to Wi-Fi but at higher speeds and over wider ranges and serving higher number of customers [16].

Table 4 shows a brief comparison between wired- and wireless communications.

Table 4. Wired vs. wireless communication [17]

	Wired Communication	Wireless Communication
Speed	Up to 200 Gbps	Up to 54 Mbps (1000 Gbps for satellite)
Reliability	High [18]	Low [18]
Flexibility§	Low	High
Efficiency	High (less signal losses)	Less (high signal losses due to interference and signal fading)
Distance	100 m – 80 km	100 m – 49 km (6000 km for satellites)
Bandwidth	0.75 – 4.7 GHz	0.85 – 3 GHz
Security	High [18]	Low [18]
Interference	Less (cables in substations are mostly isolated to prevent external signal interference and they are shielded using metallic layers to avoid internal signal interference due to EMC issues)	High (signals transfer through the air and are subject to interference from other signals as well as distortion due to surroundings and weather conditions)
Cost	High	Less

In general, communication cables are considered more secure than wireless communication networks. Information can be only intercepted at the end of the cables, while in wireless communication, information can be intercepted between the sending and receiving ends. Given that in power systems, mainly network operators have access to the sending and receiving ends, communication cables offer a

§ In terms of reconfiguration, reusability, mobility, etc.

secure mean to transfer information within the power systems. On the other hand, wireless technology offers a cheap and flexible solution for communication due to the absence of cable costs. Wireless ICT is a promising solution for data transmission if strict encryption techniques are applied.

To establish communication between two devices a set of hardware and software components are required. Beside sending and receiving hardware equipment and a communication medium, a communication protocol is required to define the rules, syntax, semantics, synchronization, and error recovery methods of communication. The following section addresses the most used communication protocols in power systems.

2.3. Communication Protocols in Power Systems

According to IEEE communications protocol is defined as a formal set of conventions governing the format and relative timing of message exchange between two communications terminals. A strict procedure required to initiate and maintain communication. This regulates the order and arrangement of Information, transfer speed or baud rate and error checking. In other words, communication protocols are enablers for data to be transmitted between two or more communication partners, where the same data format is implemented to understand each other's.

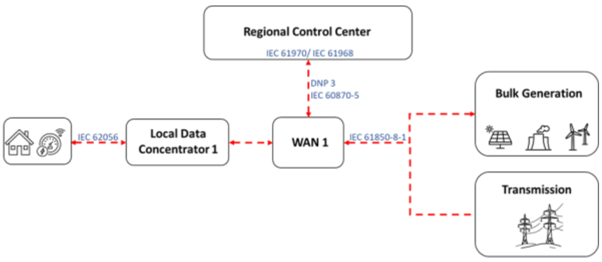


Fig. 3. Communication protocols used in modern power grids.

The following communication protocols are used in power systems to communicate between field devices and utility (see Fig. 3).

Metering:

IEC 62056 – Electricity metering - Data exchange for meter reading, tariff and load control protocol is used for communication between the metering infrastructure and WAN.

Substation and control centre:

IEC 60870-5 – Telecontrol equipment and systems protocol defines transmission frame formats and general structure of application data as well as other specification regarding functions and security. This protocol is used as standard protocol for European implementations [19].

DNP3 – Distributed network protocol is applied for communications between control centres and RTUs in substations.

Substation Automation:

IEC 61850 – Communication networks and systems in substations is widely accepted standard among different vendors which defines communication protocols for intelligent electronic devices (IED) in electrical substations. The IEC 61850 is high-level object-oriented protocol which allows devices from different vendors to communicate together. In the future, the IEC 61850 will replace other standard communication protocols including control centres and distribution automation protocols [19, 20], as it can ensure the interoperability of all components participating in distribution automation, starting from the distribution substation down to the end-user [19].

EMS:

IEC 61970 – Energy management system application interface protocol provides instructions for integration of energy management system applications developed by different vendors in control centre as well as data and information exchange with SCADA systems.

DMS:

IEC 61968 – Application integration at electric utilities.

3. Network Areas in Smart Grids

The information and communication system in SG is classified to several network areas depending on the coverage range and data rates as well as applications. In SGs there are three main network areas, Wide Area Network (WAN), Neighbourhood Area Network (NAN) and Home Area Network (HAN).

Wide Area Network (WAN):

WAN is a telecommunication network that covers a large geographic area [21]. It forms the backbone of the communication network in the power system [22]. The WAN connects different networks including bulk generation, transmission systems as well as local data concentrators to the regional control centre of the utility company (see Fig. 4). Deployable ICT are PLC, fibre optic cables, cellular networks, WiMAX, and satellites.

Neighbourhood Area Network (NAN):

NAN allows the communication between the smart meters within Home Area Networks (HAN) and the local data concentrators. The area coverage for the network area type is typically between 10 m to 10 km. Possible ICT are PLC, ZigBee, WLAN and WiMAX.

Home Area Network (HAN):

HAN is a type of Local Area Network (LAN) which allows communication between smart meters and home devices such as home automation, Home Energy Management System (HEMS), Electric Vehicle (EV) charging stations, Photovoltaic (PV) system, etc. HAN neither requires high speed data rates nor large coverage areas, typically in the range between 1 m to 100 m. Popular ICT used in HAN are WLAN, Bluetooth, and ZigBee.

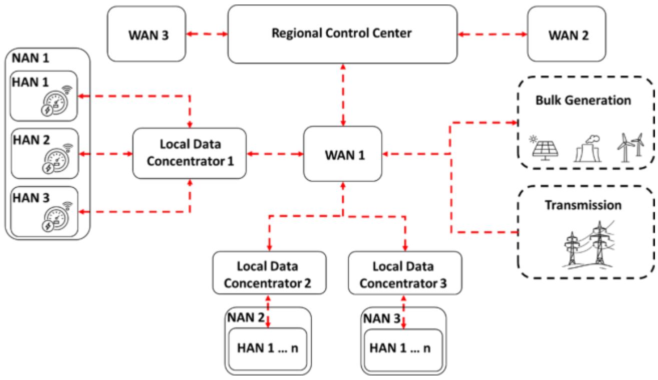


Fig. 4. Information flow in smart grids.

Fig. 4 shows the information and communication flow within smart grids. Each HAN has a group of smart appliances, such as washing machines, refrigerators, and heaters, connected to the smart meter via ZigBee communication technology. The smart meter receives live readings each 45 seconds and sends these further to the local data concentrators. The local data concentrators communicate with the WAN via WiMAX, which collects data from several power system assets and sends them further to the control centre of the utility company. The control centre receives the data from different WANs and processes them in the EMS and sends commands accordingly to balance the energy supply and energy consumption actively and economically.

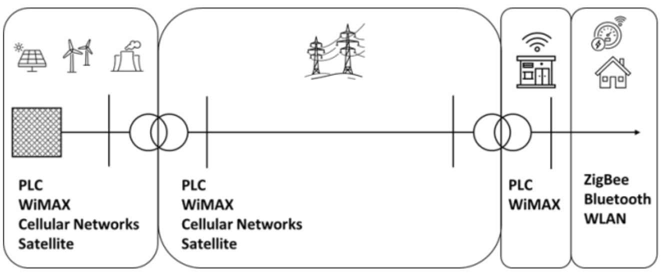


Fig. 5. ICT application areas in power systems

In Fig. 5 the classification of ICT with respect to their area of application is shown. On the generation and transmission levels the cost, security, coverage area as well as data rate are of high interest to enable real-time secure data communication between grid equipment and control centres. On the other hand, small coverage area, low data rate and low-energy technologies are used on the distribution levels.

4. Applications of Smart Grids

Monitoring and controlling of grid assets on the generation, transmission and distribution levels is one of the advantages of smart grids over traditional grids. This is only possible when using two-way, real-time, and reliable ICT. SG applications include grid monitoring (SCADA/ EMS), Advanced Metering Infrastructure (AMI), Vehicle-to-Anything (V2X), FLISR, Demand Response (DR), etc. These applications depend heavily on information and communication infrastructure.

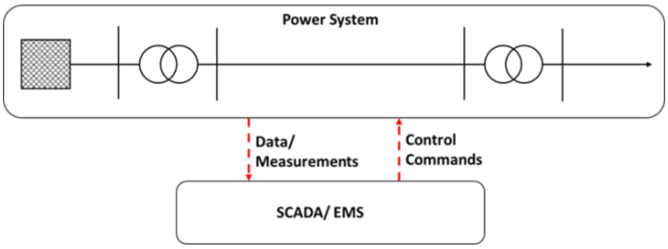


Fig. 6. Information flow in power systems.

Fig. 6 shows the information flow in the SG. The control centre, which includes the SCADA and the EMS, is the decision centre for the power system. It receives critical data and measurements from connected substations and sends back commands via grid operators. This allows optimized operation of power grids.

Grid Monitoring and Control:

SCADA and EMS are the building stones for grid monitoring and controlling systems. SCADA is a computer-based control system that integrates ICT, graphical user interface and central processing units to monitor and collect data and information from different remote field devices. SCADA and EMS together provide management information including scheduled maintenance plans, detailed schematics and Single - Line Diagrams (SLD) of the system using Human Machine Interfaces (HMI) as well as important parameters which support the network operator taking the right actions. Due to the increasing number of digital data, operations and grid complexity, new technologies such as Internet of Things (IoT) and Machine Learning (ML) are of high interest in smart grids to enable autonomous grid operations.

AMI:

AMI combines smart meters, two-way communication networks and data management systems to ensure reliable and efficient power generation and distribution. It collects measured data from wireless sensors scattered over the SG, processes them, and sends them further to the utility company. Based on these data, the utility companies can balance the generation and consumption. Additionally, AMI reduces the costs of metering and billing, and provides the customer more control over the electricity consumption, costs, and bills [23]. In 2013 EDP, one of the largest utility companies in Brazil, boosted the ICT infrastructure in the city of Aparecida with up to 8 ZigBee networks including

ZigBee coordinators and a total number of 13.800 smart meters. The smart meters receive consumption data of the household and sends the data further to the ZigBee coordinators. The ZigBee coordinators are installed on the distribution poles and send these data further to the utility company. The data are transmitted using WiMAX communication protocol or cellular networks (e.g., GPRS, GSM and 3G). The project allowed new features such as grid management, loss management as well as flexible tariff metering [24].

V2X:

V2X refers to Vehicle-to-Everything, e.g., Vehicle-to-Grid (V2G), Vehicle-to-Home (V2H), Vehicle-to-Building (V2B), etc. V2X is a technology that allows the use of the Electric Vehicle's (EV) battery to provide electric power at peak times or during times when electric power is not available. In general, EV batteries are in the range of few tens of kilowatts (kW) to hundreds of kWs. This capacity is relatively too small to be used by utility companies, but with the increasing rate of electrification and the increasing number of EVs, they can be considered as mini-storage systems connected to the grid. Thousands of mini-storage systems can provide ancillary services. ICT is a fundamental requirement to implement V2X concepts in SG. WiMAX and IEEE 802.11p are used as standard communication protocols for V2G applications. WiMAX has a coverage of up to 5 km, high data rate up to 100 Mbps and low latency 25-40 ms, while for IEEE 802.11p the coverage area is up to 1 km, data rate up to 54 Mbps and a latency of 50 ms [25].

FLISR:

FLISR is an integrated solution for distribution automation. It involves automated feeder switches and reclosers, line monitoring devices and communication technologies. FLISR enables the reconfiguration of power flow in case of fault conditions to reduce the number of affected customers and therefore increases the grid reliability and availability. ICT represents the backbone of this SG solution. [26] reported, a Canadian utility company upgraded its ICT infrastructure and used WiMAX as a communication protocol to communicate between auto-reclosers and communication devices. In fault conditions, the recloser opens and sends a status update to the neighbouring reclosers. According to the status report, the neighbouring reclosers open or close to isolate the fault, and if possible, it will reconnect through a different source, to reduce the number of affected customers to the minimum. This increases the availability and reliability of the system and hence improves the service quality.

Home Energy Management Systems (HEMS):

HEMS is an Internet of Things (IoT)-based system which receives information from different sources, such as weather information, energy price signals and customer inputs or load profiles. In general, all loads (smart appliances) and distributed generation units (PV as an example) or utility grid are connected to the HEMS. Depending on the information received from these loads and generation units, it can control and manage the electric power consumption at residence buildings [27]. Together with ICT and smart appliances, HEMSs play a vital role in energy efficiency of residence buildings and therefore one of the enablers of smart grids technologies.

Demand Response (DR):

One of the basic features of SGs is the demand response. The main purpose of DR is to adjust the consumer's power consumption, so it fits the utility generation curve using price signalling through smart meters. Smart appliances and ICT are key enablers of this basic feature in SG.

5. Challenges of ICT in SGs

Cybersecurity:

The accelerating adoption of information and communication technologies to digitalize the energy system increases the vulnerability to cyber-attacks. Until recently, power system operations and controls were carried out manually and mechanically. Modern and next generation power systems use ICT to receive information and measurements from sensors and based on these information operation decisions can be made (see Fig. 6). These bi-directional exchange of information flows in communication channels can be intercepted at the end of the channel (in case of wired communication) or along the whole channel (in case of wireless communication). No communication technology is immune to cyber-attacks. The so called smart-home-appliances together with digital grid equipment and Distributed Renewable Energy Resources (DER) provide a large attack area for threat agents. Therefore, many countries are embracing new regulations, laws, and roadmaps to protect the energy system from cyber threats.

Data privacy:

In addition to the advantages associated with SGs comes the risk of data privacy as digital devices provide more data to the network operator. Many SG features and applications such as demand side response involve sharing energy consumption data and personal activities with the utility companies [28]. Another application is home energy management systems, that can be controlled via mobile apps, which is connected to the smart meter. All home appliances including personal devices such as mobile phones and laptops are interconnected to the same HAN and hence the risk of accessing sensitive information is expanded. As a result, network operators and utility companies need to integrate privacy policies in their system to regulate how the private information is used, distributed internally, shared with third parties, and stored [29].

Reliability:

The electricity demand is growing faster than renewables, driving strong increase in generation from fossil fuels [30]. In the context of SGs, reliability is a major concern for all stakeholders as well as consumers due to the complexity of the system and the increasing demand. In addition to cyber-security concerns, the reliability of ICT plays a crucial role in SGs. In [31] a case study was conducted on the reliability of ICT in power systems and has shown that RTUs has a high repair time and low repair rate. This means that a failure in one RTU will cause interruption in communication with other devices attached to it and hence losing control of these devices. The same impact will take place in case of hardware as well as software failures. Distributed Renewable Energy (DRE) represents another big challenge due to its intermittent nature.

Cost:

As indicated in the above sections, SGs involve new generations of different technologies and different devices [32] which increase the costs dramatically. Cost is one of the major reasons that's holding back SG developments. Utility companies invest in renovation and rehabilitation of old equipment and devices. SGs require building a new infrastructure for ICT as well as reshaping the network topologies and adopting new technologies which are not familiar to them.

Operation:

In general, network operation is very challenging and this challenge increases by the increase of the network's complexity. The integration of DRE and battery systems as well as the adoption of new loads with dynamic characteristics require new operational approaches. Some research institutes are focusing on self-operating grids (autonomous grids) and implementation of software-tools which can be integrated in the control centre to help the network operators make quick and right decisions. These tools are based on machine learning and IoT.

6. Conclusion

Wireless communication technologies are offering a cheaper solution but only if reliable encryption and authentication techniques are applied. Moreover, they present an ideal opportunity to integrate smart appliances and smart meters for residence applications to increase the energy efficiency at residence buildings. On the other hand, challenges regarding cyber security, data privacy, reliability, market regulations and cost must be addressed as quickly as possible to enable integration of SGs and speed up the energy transition process. New technologies and applications such as SCADA/ EMS, AMI, FLISR, V2X, HEMS, DR, etc. can increase the energy efficiency and optimize the network operation processes.

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