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Faults in Smart Grid Systems: Monitoring, Detection and Classification

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Abstract

Smart Grid (SG) is a multidisciplinary concept related to the power system update and improvement. SG implies real-time information with specific communication requirements. System reliability relies on the best capabilities for monitoring and controlling the grid. Among other aspects, SG applications involve three main challenges, sufficient real-time capable measurement units, managing large data sets, and two-way low-latency communications. Considering fault detection and classification a key factor to SG reliability, this work provides a systematic review of SG faults from the most significant research databases and state-of-the-art research papers aiming at creating a comprehensive classification framework on the relevant requirements. This paper includes in detail the classification of different fault scenarios in a comprehensive framework that involves system-level of application, *e.g.*, transmission, distribution, commercial, DG, and EV. To this end, We analyze and indicate relevant topics for future developments related to the monitoring and fault detection and classification in SG systems.

Keywords: Smart Grid; Electric power system; Fault Monitoring; Fault detection; Fault Classification; 5G Communication Systems

1. Introduction

In general, a fault is a condition of something reporting that it is not working correctly. In an electric power system, a fault is usually associated with an abnormal electric current, specifically, a short circuit is a fault in which current exceeded normal operating conditions. Power systems evolution to smart grid implies improving the network of transmission lines, equipment, controls and new technologies to integrate information and communications technology into every aspect of electricity generation, transmission, delivery, and consumption to minimize environmental impact, enhance markets, improve reliability and service, reduce costs and improve efficiency.

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Acronyms

μSG micro-SG
1PPS One pulse-per-second
ADC Analog-to-Digital conversion
AI Artificial Intelligence
AMI Advanced Metering Infrastructure
ANN Artificial Neural Networks
BLER Block Error rate
CB Circuit Breaker
CBG Code Block Group
CES Conventional Energy Systems
CIS Consumer Information System
CT Current Transformer
DA Distribution Automation
DER Distributed Energy Resources
DFT Discrete Fourier Transform
DG Distributed Generation
DMS Distribution Management System
DoS Denial of Service
DR Demand Response
DSO Distribution System Operators
DSP Digital Signal Processors
EE Energy-Efficient
EMS Energy Management System
eMTC Enhanced Machine-Type Communication
EV Electrical Vehicle
FAN Field Area Network
FD/L-SG Fault Detection and/or Location in SG Systems
GPS Global Positioning System
H2H Human-to-Human
HAN Home Area Network
HMI Human Machine Interface
IAB Integrated Access Backhaul
ICT Information and Communication Technology
IED Intelligent Electronic Device
IGBT Insulated-Gate Bipolar Transistor
IoE Internet-of-Energy
IoT Internet-of-things
IoTG Internet-of-things-Grid
IP Internet Protocol
IRIG-B Inter-Range Instrumentation Group-B
ISP Internet Service Providers
IT Information Technology
LoS Line of Sight
LR-WPAN Low-Rate Wireless Personal Area Networks
LTE Long-Term Evolution
M2M Machine-to-machine
MDMS Meter Data Management System
ML Machine Learning
mMTC massive Machine-Type Communication
MPU Main Processing Unit
MU Merging Units
NAN Neighborhood Area N etwork
NB-IoT Narrowband Internet-of-Things
NN Neural Network
NSP Network Service Providers
NTP Network Time Protocol
P2G Phase to Ground
P2P Single-Phase to Phase
PDC Phasor Data Concentrator
PEM Proton Exchange Membrane
PLC Programmable Logic Controller
PLC Power Line Communication
PMU Phasor Measurement Units
PP2G Two-Phase to Ground
PPP Three-Phase
PPP2G Three-Phase to Ground
PQA Power Quality Analyzers
PSFB Phase-Shifted Full-Bridge
PTP Precision Time Protocol
PV Photovoltaic
PWM Pulse Width Modulation
QoS Quality of Service
RA Random Access
RACH Random Access Channel
RAN Radio Access Network
RF Radio frequency
RIAPS Resilient Information Architecture Platform for Smart Grid
RTU Remote Terminal Units
SA Service and System Aspects
SCADA Supervisory Control and Data Acquisition
SG Smart Grids
SM Smart Meters
SMPS Synchronized Phasor Measurement System
SPM Synchro-Phasor Measurement
SS Smart Sensor
ST Smart Transformer
SV Sampled Values
SVM Support Vector Machine
SyG Synchronous Generators
TSN Time-Sensitive Networks
URLLC Ultra-Reliable Low-Latency Communications
VT Voltage Transformer
WAMS Wide Area Measurement System
WAN Wide Area Network
WASA Wide-Area Situational Awareness
WiMAX Worldwide Interoperability for Microwave Access

Smart Gridss (SGs) describe a new generation of the smart electric network model that integrates actions coming from all connected end-users. This infrastructure provides bidirectional communications between end-users and the grid operator, extending the energy grid accessibility. For instance, consumers such as households and enterprises are now digitally connected to the Information and Communication Technology (ICT) infrastructures of Distribution System Operatorss (DSOs) through smart meters via a Wide Area Network (WAN) network [1]. Smart meters set the separation point between the DSO-ICT infrastructure and the Customer Premises Network. Indeed, SG aggregates increased automation and control capabilities to the transmission and distribution grids, also adding a new layer of system complexity that offers new challenges for ensuring the reliability and safety of operations.

The new SG system model should include modeling and identification of real-world SG states, collecting and processing heterogeneous information coming from various information systems [2]. Considering classification models, the SG systems should be able to identify fault states from the decision function, interpreted as the reliability of the classification. The *power grid faults* model is paramount to discriminate faults from standard functioning states. The *protection* schemes for SG and Micro-SGs (μSGs) consider the concept of Internet-of-Energy (IoE) [3, 4] utilized for the operation and coordination of protection to obtain an efficient and dynamic infrastructure. The process of identifying/classifying faults based on the data information exchanged among relays and Phasor Measurement Unitss (PMUs), is accomplished into a centralized and dynamic infrastructure.

SG demands real-time state estimation utilizing synchronized PMUs at high sampling rates [5]. Wide Area Measurement System (WAMS) explores those PMU data requiring a novel communication infrastructure support. WAMS aims to identify and neutralize power grid disturbances in real-time applications, consequently requiring a communication infrastructure capable of integrating a high number of PMU devices with exceptional reliability and ultra-low latency and provide backward compatibility to legacy measurements from Supervisory Control and Data Acquisition (SCADA) systems [6].

Existing technologies such as Energy Management System (EMS), Distribution Management System (DMS), and SCADA have been updated to adapt them to SG, alongside the integration of new technologies. Many of these supporting communication infrastructures, particularly WAN communications, are provided by telecommunication operators or Internet Service Providerss (ISPs). Therefore these infrastructures will most likely be shared among multiple companies, ranging from the reliability of the whole power system to new cyber-security risks.

Communication networks allow the "smart" aspects of the power grids, providing real-time knowledge of the grid, perform actions instantaneously when required, and gather customer consumption information. These vital assets have to be taken into account especially as far as security is concerned for several reasons: the data they transport, the increasing attack surface, the possible cascading effects that an attack can generate in the rest of the grid, etc. The arrival of 5G communication networks will considerably promote the requirement of the distributed data acquisition and processing services for WAMS systems [7]. Also, the awakening of massive Machine-Type Communication (mMTC) services will provide support for a large-scale deployment Advanced Metering Infrastructure (AMI) [6]. This survey also explores aspects related to the communication networks and the inter-connectivity compliance in SG, identifying vulnerabilities, risks, and threat agents. Table A.12 in the Appendix A summarizes the relevant published research inside the scope of SG systems.

1.1. Scope of the Survey

The main published surveys and tutorials on Fault Detection and/or Location in SG Systems (FD/L-SG) are compiled and compared in this subsection, in terms of the range of application, covered topics, and trending research.

Existing surveys: Table 1 lists the existing surveys related to fault detection and/or location in the SG systems context. Most of the published surveys do not contain a wide range of applications. The currently published surveys either focus on particular components of the SG system or do not cover monitoring components or prominent communication technologies to achieve Quality of Service (QoS) requirements and constraints in SG systems.

Table 1: A list of surveys in fault detection and/or location for the SG systems context

Year	Ref.	Description
2017	[8]	A review of fault location and outage area location methods for distribution systems
2016	[9]	A survey on intelligent system application to fault diagnosis in electric power system transmission lines
2017	[10]	A comprehensive study on different types of faults and detection techniques for solar PV
2018	[11]	Fault detection and prediction in smart grid systems
2018	[12]	A survey on fault detection, isolation, and reconfiguration methods in electric ship power systems
2018	[13]	A review of the principles of fault location and indication techniques and their application considerations

To fill this gap, in this work We investigate in-depth, the role of sensing and monitoring within FD/L-SG scenarios. We have covered the latest surveys on FD/L-SG and related papers until Q2 2020. Note that detection/location depends on many system components and different system-level of application, therefore covering the entire spectrum of applications to evaluate future research directions is out of the scope of this paper..

We focus on future topics related to monitoring and communication techniques for SG systems.

Summary of the contributions: This survey covers different aspects of fault detection in SG systems. The goal is to indicate relevant topics for future development to bridge the gap between legacy and future fault detection techniques. The main contributions of this work can be summarized as follows:

1. We provide a systematic review of SG faults from the most significant research databases and state-of-the-art research papers aiming at creating a comprehensive classification framework on the relevant requirements.
2. We conduct an in-depth and comprehensive survey on the role of several components of the legacy power system and SG systems.
3. We discuss in detail the classification of different fault scenarios in a comprehensive framework including system-level of application, *e.g.*, transmission, distribution, commercial, Distributed Generation (DG), and Electrical Vehicle (EV).

4. We analyze and indicate relevant topics for future developments related to the monitoring and fault detection and classification in SG systems.

SG systems monitoring and fault detection are essential for the QoS guarantees in SG applications and therefore need close attention. After covering the SG fault scenarios we discuss the existing FD/L-SG techniques and offer a classification framework to evaluate whether is applicable for specific implementations. Then a tendency on using learning-based methods in addressing fault detection for SG systems is demonstrated. Later We identify topics that were not addressed prior discussed. We then dive deeper into the communication techniques that address the challenges of sensing technologies for monitoring. We also outline future research opportunities and direction. The graphic illustration of the scope of this survey is shown in Fig. 1. Finally, based on the handled reports regarding faults in SG systems, considering monitoring, detection, and classification, we identify the existing challenges and future research directions.

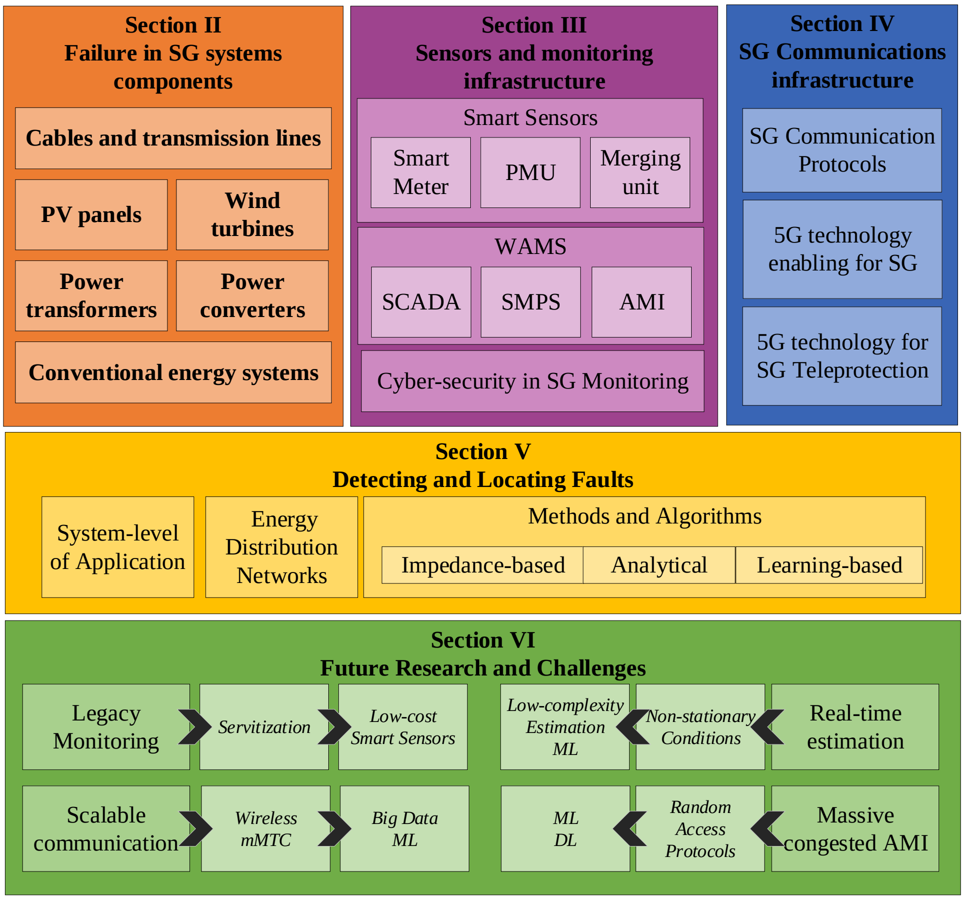

Figure 1: Composition and SG topics discussed in this survey

The remainder of the paper is organized as follows: Section 2 presents Failure in legacy components brought to the SG systems context. Next, Section 3 describes the sensor and monitoring infrastructure, while Section 4 develops communication definition into SG and discusses the role of 5G technology as an enabler for SG . Section 5 aggregates concepts and procedures associated with the SG faults detection and location in the Smart City context.Next, Section 6 describe lessons learned and future research directions in FD/L-SG. Finally, Section 7 offers the main conclusions.

2. Failure in SG systems components

The demand for electric power is growing within the arrival and establishment of the smart cities and Industry 4.0. Fault analysis is essential to enhance performance and minimize interruptions in the smart power system. It is fundamental to detect, locate, and clear faults at any power system level to keep the power system operating in normal condition. This task requires intelligent control to perform quickly and efficiently [14].

Next, we describe the concepts in a physical framework approach, avoiding evaluation of the software framework (some times called Resilient Information Architecture Platform for Smart Grid (RIAPS)) which includes architectures for a highly resilient, hierarchical fault management scheme. The problem of reliability and resilience in decentralized, real-time, embedded systems with respect to fault detection and mitigation in accordance with the physical layer is remarkable, deserving massive researches in the future.

Faults that can arise at different layers of the system can be categorized as follows:

1. **Physical devices/components fault:** These faults occur when a physical element does not function properly.
2. **Communication fault:** These faults occur in communication devices/channels. Related to faults in the physical links, or failure establishing communications in a critical time period.
3. **Software/Hardware-level fault:** These faults occur when a component of the control center fail command and/or operation.

On the physical level, the power grid itself is intended with the $N-1$ power system rule, meaning that any physical component, *e.g.*, a breaker, a transformer, a transmission line, etc., can fail, yet the power system endures operational [15]. This principle carries over to the sensors and actuators, *i.e.,* there is sufficient redundancy in the system.

Fault management techniques rely mainly on the communication network of a SG system. Furthermore, fault management is essential to reduce the synchronization problem and to improve the system incoming. Nevertheless, most fault management techniques demand a data processing center to monitor and analyze the operation of the system in real-time, as well as fault indicators, local automation, and communication devices. Additionally, it is important to detect and locate the fault rapidly enough to avoid a complete collapse of the system.

Faults in the electrical infrastructure of the SG include various components of the micro-grid and also the causes and effects of the faults, Fig. 2. The following subsections provide details of these failure modes for various physical systems and components inside the SG architecture.

2.1. Cables and transmission lines

Power cables constitute the critical links between the generation sources and loads, including transmission and distribution-level lines. They typically carry low-voltage which is stepped down from the transmission grid or generated from the distributed generation systems. Power

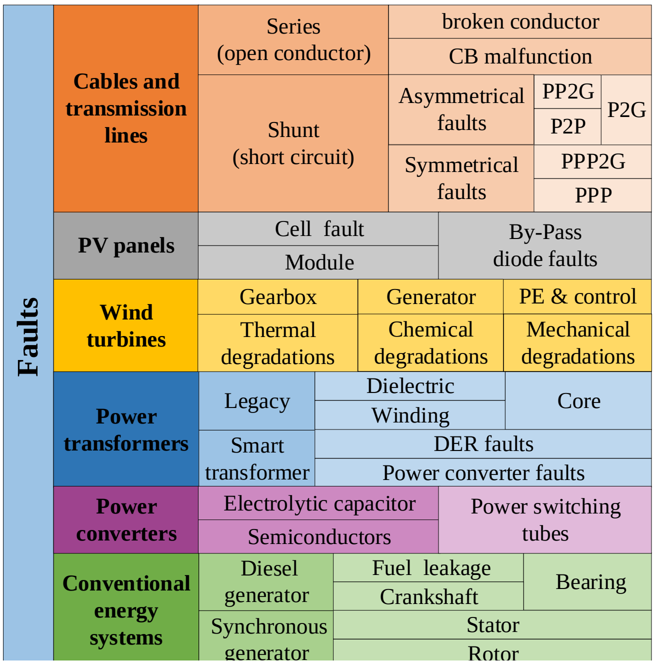

Figure 2: Types of faults in the SG infrastructure

cables are usually installed underground while transmission lines are laid overhead [16, 17]. Underground cables are constrained to mechanical faults, thermal runaway due to the compacted soil playing as an insulator, and typical wear and tear. Overhead lines, on the contrary, are predisposed to the natural causes that can cause faults due to lightning strikes, icing, breakage as a result of animal or tree obstructions, short circuits, overloading, aging, human actions, or simply the absence of maintenance.

Faults may be classified into two types, i.e. series (open conductor) faults, and shunt (short circuit) faults. Differences among the impedances of three phases indicate a series type fault, which is usually caused by the interruption of one or two phases. Series faults in transmission/distribution lines may occur due to a broken conductor or a Circuit Breaker (CB) malfunction in one or more phases. Short circuit faults are divided into two types, i.e. asymmetrical faults, and symmetrical faults. The asymmetrical or balanced fault affects each of the three phases equally. An asymmetric or unbalanced fault does not affect each of the three phases equally. Asymmetrical faults Phase to Ground (P2G), Single-Phase to Phase (P2P), and Two-Phase to Ground (PP2G), and symmetrical faults are Three-Phase (PPP) and Three-Phase to Ground (PPP2G) faults.

Single Line-to-Ground Fault: This fault occurs when one of the three phases physically connects with the ground causing a short circuit. *Double Line-to-Ground Fault:* This fault is similar in effect to the single line-to-ground except that in this case two of the three phases come in physical contact with the ground causing short circuits. *Line-to-Line Fault:* This fault occurs when a combination of two out of the three phases connects causing a short circuit between them. This is typically caused when the cable insulation degrades and breaks resulting in openly exposed wires.

2.2. *Photovoltaic (PV) panels*

Photovoltaic (PV) panels employ solar radiation to generate power for the micro-grid. Their construction consists of elements such as glass, metals, polymers, and semiconductors. Common faults that occur in PV panels include the following:

1. *Cell faults:* these faults can be additionally classified into three main faults: (i) open/short-circuited cells, (ii) hot-spot faults, and (iii) degeneration faults. Open/short-circuited cells are induced when a cell disconnects or shorts ending in a loss of the cell. Hot-spot faults are prompted when the panel is partially shaded or damaged which results in a decrease in the cell current. Degeneration faults are effected when the cell series resistance rises due to over exposer, a decrease in cell shunt resistance due to crystal damage/impurities in the inter junction, trash accumulation on the surface, mismatched cells, and/or overheating.
2. *Module faults:* these faults typically consist of open or short circuits, fractured glass, and delamination. Most of the time, these faults occur because of manufacturing defects, mechanical loads (such as snow accumulation), corrosion, natural occurrences, and degradation of the anti-reflection coating of the cells.
3. *By-Pass diode faults:* these faults occur either due to a short or open circuit. If an open circuit fault occurs, the cell may be subjected to hot spots while short circuit faults will result in decreased generation efficiency. These typically occur due to an overheated diode.

The failure modes described above corresponding to the PV panels result in decreased output power leading to reduced voltage and current signals in the micro-grid.

2.3. *Wind turbines*

Wind turbines represent another renewable energy resource that generates power from the wind. The turbines are subject to various faults in the following subsystems:

1. *Gearbox:* faults befalling in the gearbox are usually bearing faults which are the major problem of wind turbine failures since they are in multiple subsystems. Bearing faults typically fall below two categories: inner/outer race faults or ball faults, which occur from abrasive wear, corrosion, lack of lubrication, and accumulation of debris.
2. *Generator:* the generators can fail because of faults in the bearings, stator, and rotor. Bearing faults described above are similar. Stator and rotor faults are mainly open/short circuits, abnormal connections in windings, broken rotor bar, air eccentricity, and demagnetization. Stator faults appear because of insulation degradation which results in inter-turn short circuits, while rotor faults occur from broken or shorted windings. Faults in the generator produce unbalanced voltages and currents, decreased average torque, excessive heating, and low generation efficiency.
3. *Power electronics and electric control:* faults here essentially occur within the semiconductor devices and include short or open oxygen reaction. Their construction consists of the membrane, electro-catalyst, catalyst, and gas diffusion layers which tend to degrade over time. The following degradations occur in these layers:
    - *Mechanical degradations:* These are produced by breaks because of incorrect membrane electrode construction and/or humidity cycling.
    - *Thermal degradations:* these are commonly induced by a change in hydrations in the Proton Exchange Membrane (PEM), either due to flooding or dehydration. This usually occurs when the fuel cell is operating at temperatures outside of the recommended operating range.

- *Chemical degradations:* These occur due to the combustion of hydrogen and oxygen. When they combust, foreign cationic ions may form causing the layers to degrade.

PEM fuel cells also contain three other components that suffer from degradations as well. These are the bipolar plate, a sealing gasket, and a compressor motor.

2.4. *Power Converters*

The power electronics converters widely used in the fields of energy conversion, in which the Phase-Shifted Full-Bridge (PSFB) DC-DC converters play a crucial role in multiple cases such as aeronautics, astronautics, hybrid EV applications, among others. Power switching tubes is one of the most vulnerable components in power electronic converters because of over-voltage, over-heating, or erroneous signal [18].

The most critical elements of power converters are the electrolytic capacitors and semiconductors. Due to their cost, size, and performance, capacitors are the usual choice for smoothing the output voltage in DC-DC power converters. Nevertheless, according to [19], electrolytic capacitors frequently determine the life-time of Pulse Width Modulation (PWM) converters and are responsible for more than 50% of their failures. The fault of the power semiconductor comprehends a short-circuit fault and open-circuit fault. Short-circuit faults, usually protected by the standard protection circuit, are considered as the most dangerous, and the Insulated-Gate Bipolar Transistor (IGBT) will shut-off instantly once short-circuit fault is detected. On the contrary, though the open-circuit faults, they ordinarily last for some time and may cause subsequent damage to other equipment.

2.5. *Power Transformer*

Power transformers are fundamental components of power systems, and damage to or failure of transformers causes significant economic and social injuries. Consequently, performing efficient and reasonable transformer fault diagnosis is essential for the safe and secure operation of power systems. An in-service transformer handles numerous harmful operating conditions that can break down the insulating materials and release gaseous decomposition products dissolved in the oil [20].

Transformer oils render electrical insulation under high electrical fields; any significant reduction in the dielectric capacity may indicate that the oil is no longer capable of performing this vital function. Even a minor fault, *e.g.* damage to core bolt insulation, local overheating, etc., creates an arc that causes a slow generation of gas in the oil. All faults in the transformer core and windings result in the localized heating and decay of oil. The most common windings faults are failures between primary and secondary windings (short circuit) of the same phase and short-circuit between the turns of the winding. These faults normally result from a dielectric failure due to the aging of insulation material (also increase due to overloads). When core insulation becomes defective or the laminated structure of the core is bridged by any conducting material increases sufficient Eddy current to flow causing serious overheating. The insulated core bolts tight the transformer core. If the insulation of these bolts fails, it provides an easy path for stray current leading to overheating.

2.5.1. *Smart Transformer (ST)*

The Smart Transformer (ST) is a device for active MV to LV substations replacing the classical electromagnetic transformer by an AC/DC/AC power conversion frame with a high-frequency transformer. This framework makes ST sensible to those failures present on power converters. Those STs support loads during a partial disconnection in an HV/MV power system. For a system fault, the storage unit placed in the ST and the Distributed Energy Resources (DER) located downstream from STs provide active power to other MV feeders [21].

2.6. *Conventional Energy Systems (CES)*

Conventional Energy Systems (CES) include power plants using fossil fuels (natural gas, diesel, coal, etc.). In SG architecture CES are used to back-up renewable power generation. Diesel generators are currently used to back-up renewable energy generation. Minimal research has been published on the faults for diesel generators; however, the engine and electric generator faults have been reported. Diesel engines have the following faults:

- *Fuel leakage:* this occurs from the growth of small holes in the system and causes air contamination. This results in gas pressure decreasing, which further leads to reduce combustion efficiency.
- *Bearing faults:* these faults are the same as those described in an outer race and ball faults which are caused by increased mechanical loads, wear, and etching.
- *Crankshaft faults:* the main fault for a crankshaft is the initiation and growth of cracks. This is caused because of corrosion or poor assembly and may lead to a reduced ability to generate rotational energy. As cracks grow, the effects of the fault increase until the shaft breaks in half.

The faults associated with diesel generators cause a decrease in their performance which can be observed as current and voltage drops.

2.6.1. *Synchronous Generators (SyG)*

Power systems mainly fed by the synchronous generators of large thermal power plants. The fault behavior of these Synchronous Generators (SyG) is well defined: when a fault occurs a SyG responds as an ideal voltage source behind an impedance and inject fault currents up to 5–10 PU [22].SyGs are one of the most important elements of power systems. Unlike other power system components, SyGs need protection from several different types of faults and abnormal operating conditions, such as stator winding faults, overload, unbalanced operation, loss-of-excitation, loss-of-synchronism, and motoring. Modern digital signal processing techniques and advanced model-based analytical methods improve generator protection [23], especially from a potential stator fault. This type of fault may cause severe damage to the generator.

The most common type of fault that SyGs are subject to is ground faults in stator windings. When SyGs are grounded with high impedance, it is difficult for differential protection to detect faults on stator winding since small fault currents are generated. The faults for these components are single/multiple phase short circuits, inter-turn short circuits, saturation, grounded windings, rotor bending/cracking, air eccentricity, and permanent magnet degradations [24]. Such faults occur because of insulation damages/degradation, a reduction in lubrication, overheating, and manufacturing defects, leading to unbalanced voltages and current harmonics, a reduction in the generation efficiency, and current phase shifts.

The various failure modes of different micro-grid components described in this section illustrate the fault universe in SG architecture. We understand those are limited categories in the vast power system outline.

3. Sensors and monitoring infrastructure

Sensors allow the grids to be "smarter" and play a critical purpose in real-time monitoring and control of power transmission and distribution systems. Besides, sensors are fundamental for maintaining grid health and stability. Grid control relies on the measurement and monitoring of electrical parameters in the transmission and distribution networks. Sensors measure several classes of physical parameters at different system-level of application, including power generation, transmission lines, substations, distribution lines, energy storage, as well as consumption and customer profile. Among those sensors, Current Transformers (CTs) and Voltage Transformers (VTs) keep large partition between legacy and smart power system installations. Recently, the number of measuring devices and sensors in the power grid has increased quickly, within PMUs and Smart Meterss (SMs), also named AMI, as most extended devices demanding attention for future research [11]. Following, we present a non-exhaustive list of sensor devices commonly used in power systems [25]:

- Merging Unitss (MUs)
- temperature sensors
- humidity sensors
- accelerometers
- rain gauges
- internet protocol (IP) network cameras
- pyranometers and pyrheliometers (solar irradiance)
- weather stations
- sonic anemometers
- partial discharge sensors
- gas sensors
- ultrasound and ultra-high frequency sensors
- torque sensors
- discharge rate sensors
- load-leveling sensors
- occupancy sensors
- Power Quality Analyzerss (PQAs);

Fig. 3 depicts an SG overview that includes crucial monitoring devices (PMUs and SMs), whether communications and power links exist among all-important connections.

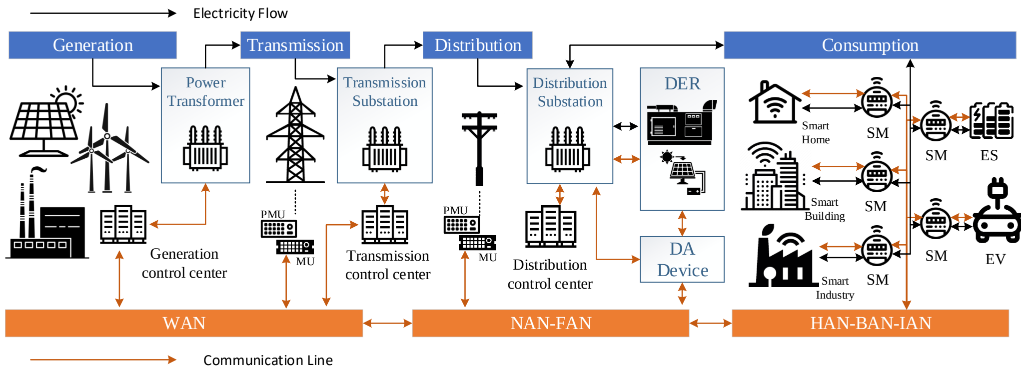

Figure 3: Smart Grid infra-structure overview, including monitoring key devices.

With the wider deployment of PQA and PMU devices, the SG enables real-time monitoring through an effective communication network. This allows the continuous evaluation of the current state of the grid, indicating congestions, frequency oscillations, and overall load distribution [26]. Empowering real-time application of estimation algorithms for fault diagnostic to reduce fault recurrence. Better monitoring solutions and predictive methods can increase the possible utilization of the existing grid.

SG continually produce data such as voltage, current, phase angle, power (kW, kVA, kVAR), temperature, type of grid connectivity, and statistics on supply and demand. In their primary form, such raw data signals are noisy, verbose, and require large amounts of memory to store. Therefore, these data signals require conversion into informative features for meaningful and timely analysis [27].

Assembling the power grid smart relies on the capacity to recognize the unprecedented penetration of sensing data to draw insights into the system's behavior and automate the available controls. With these volumes of data collected increased, new architectures, concepts, algorithms, and procedures will be necessary to obtain a smarter system. The risen volume of measurement data from the power grid, in combination with tending methods within machine learning [28], gives innovative possibilities in terms of fault detection and mitigation [29]. Table 2 summarizes the data sources characterization, which contribute to qualitatively assess the SG trending behavior. Legacy sources still represent an important portion of the data origins. Moreover, the tendency of incorporating data generated from the new AMI and PMU devices for fault detection/location is another important direction to be considered. Reliability Improvement represents a challenging task whether a massive number of devices arises in SG systems.

The figure of merit reliability-*vs*-costs measures the impacts of a monitoring system. In SG system failures rise severely for smart monitoring if the availability of this system decreases progressively [90]. For the utility, expenses limitations create an optimization framework requirement to evaluate the annual cost saving with a minimal smart monitoring infrastructure.

WAMS is an advanced measurement technology that consists of advanced information tools, operational infrastructure which facilitates the operation of the complex network by collecting data. It provides complete monitoring, control and protection. In this section, the chief components of the Wide Area System are explained. PMU is an enabler of WAMS, which prevents the power network from any blackout. The SCADA, PMU, and AMI are explained in the sequel.

Table 2: Data source for fault detection/location in SG systems

Source	Reference
Miscellaneous data (Historical, operation)	[30, 31, 32, 33]
AMI	[2, 34, 35, 36, 37, 38, 39, 40, 41, 42, 3, 43, 44, 45]
Legacy Sources (CT, VT, DFR)	[46, 47, 14, 48, 30, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 32, 61, 62, 63, 64, 65, 66, 67, 68, 69, 47, 70, 71, 72, 73]
PMU	[74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88]
Other (GOOSE, TWITTER, SCADA)	[89, 33, 43]

Important WAMS applications include a) detection of loss in synchronism; b) temperature identification; c) power system restoration; d) phase angle monitoring; e) voltage stability monitoring; f) line thermal monitoring; g) power oscillation monitoring; h) power damping monitoring [91, 92].

Microgrids are self-governing electricity environments that operate within a bigger electrical system. They can respond to a crisis or recommend the best operation response inside the necessary time frame to manage local problems when required. Centralized power-sharing, dispatching, and frequency/voltage restoration depends on reliable and optimal monitoring operation of the microgrid. The presence or absence of DG units affects fault currents that flow through the feeders [93]. Therefore, Intelligent Electronic Devices (IEDs) protect the grid adapting protection settings to overcome new fault characteristics in the microgrid.

3.1. Smart Sensors (SSs)

Smart Sensors (SSs) are sensors with built-in intelligence deployed in power grids, which include temperature sensors, pressure sensors, humidity sensors, weather stations, current sensors, and voltage sensors, among others. SSs are sensing devices with digitalization capacity and digital information processing functionalities. SSs may communicate using standardized communication protocols, such as the IEEE 1451 family of Smart Transducer Interface Standards, IEEE 1815 Standard for Electric Power Systems Communications - DNP3, IEEE C37.238 PTP Power Profile, and others.

Figure 4 represents a general model of SSs to achieve requirements for SGs. A SS contains a set of sensors, the Main Processing Unit (MPU) with an internal clock linked with an optional external time reference, and a network communication module. The main basic skills of a smart sensor can be defined by four modules:

1. sensing by means of sensors;
2. processing module composed by: analog signal conditioning, Analog-to-Digital conversion (ADC), and sensor data processing;
3. timing and synchronization by an internal clock with optional external time reference;
4. network communication module for communicating with the outside world

The sensors provide electrical signals based on physical phenomena they measure, such as voltage and current of power lines in microgrids. The internal clock generates the timestamp for sensor data and synchronizes with the external time references, such as Global Positioning

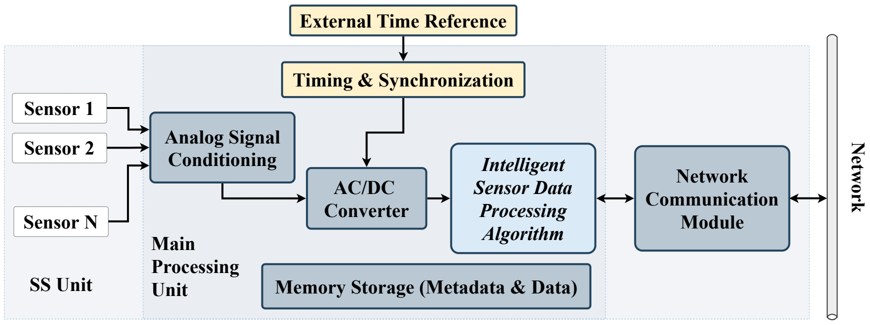

Figure 4: A general SS representation for SG

System (GPS), One pulse-per-second (1PPS) , Inter-Range Instrumentation Group-B (IRIG-B), IEEE 1588 Precision Time Protocol (PTP), or Network Time Protocol (NTP). Later the analog signals are calibrated and conditioned in the processing module, an ADC transforms the signals into digital form, while the processing module processes the data based on metadata as well as applying intelligent algorithms simultaneously under time-synchronized events aiming at improving sensing and measurement precision. Finally, a network communication module executes sensor applications via wired (serial or Ethernet) or wireless (IEEE 802.11a/b/g/n/ac, Worldwide Interoperability for Microwave Access (WiMAX) or 3G/4G/ Long-Term Evolution (LTE)/5G cellular networks) communication infrastructure.

3.1.1. Smart Meter (SM)

A SM follows a conventional electricity meter, which has only the feature of measuring the consumed electricity. Smart meters are ICT-enabled machines that trace a large number of information, e.g., features of consumption patterns over time. SMs further enable dynamic pricing in the electricity sector, where so far only one (fixed price per kilowatt-hour) or a maximum of two price levels (day and night supply) have been commercially available so far. Moreover, SMs allow the customer to choose to switch the consumption to off-peak times and save money considering the electricity price will be lower. This is even possible to be automated since devices, *e.g.*, freezers, dishwashers, washing machines, in private households as well as industrial coolers and high-energy-consuming machines, can be allowed to be directly steered by the energy price or even the energy supplier in order to smoothen the demand curve.

3.1.2. Phasor Measurement Unit (PMU)

The PMU is a device that measures the phasor of the current and voltage of the connected bus. It makes use of the GPS receiver to collect the data from the buses located at various places. The collected data are sent to the control unit through the Phasor Data Concentrator (PDC). The PMU's provide real-time time-synchronized data and high resolution for advanced applications, such as wide-area situational awareness, state estimation, monitoring system dynamics, and validating system models. Using ADC, the data samples are taken from the AC waveform and Discrete Fourier Transform (DFT) is applied. Concerning the common reference axis, the voltages of different buses are compared and monitored [94].

The PMU is a microprocessor-based device using the ability of the Digital Signal Processors (DSP), which measures 50/60 Hz AC waveforms at a typical rate of 16-64 samples per cycle [95].

These PMUs are optimally placed at different substations which are able to provide time-sampled positive sequence voltages and currents of all the monitored buses. The analog input signals for the voltage and current are supplied by the instrument transformer. For the full benefit of the Synchro-Phasor Measurement (SPM), the architecture involves PMUs, communication links, PDC. It is worth noticing that the recent commercialization of the GPS with the accuracy of timing pulses in the order of 1 microsecond ($1\mu s$) is made possible by many industries [78, 11]. By using $1\mu s$-PMUs, a high degree of accuracy in monitoring and faults detection is achieved.

3.1.3. Merging unit (MU)

The MU is a device that enables converting the analog signals from the conventional CTs and VTs into sampled/digital values, merging (align) multiple phases together based on time synchronization and transmit the Sampled Valuess (SVs) to protection relays through networks based on the International Electrotechnical Commission (IEC) 61850-9-2 standard protocol. Indeed, the MUs provide real-time status of power grids.

A key challenge confronting electrical grids is the communication interoperability of these smart sensors. A set of existing standard communication protocols for SM-, PMU- and MU-based SSs, and general purpose SSs are listed in Table 3.

Table 3: Common interface standards for SS

Smart Sensors	**Interface Standards**	**Network Connections**	
		Wired	*Wireless*
PMU	IEEE 1344 IEEE C37.118.2 IEC 61850-90-5	TCP/IP UDP/IP RS232 Optical	3G/4G/LTE Cellular WiFi WiMAX
MU	IEC 60044-8 IEC 61869-9 IEC 61850-9-2	TCP/IP UDP/IP Optical	3G/4G/LTE Cellular WiFi
SM	IEC 62053-23 IEC 62056-21	TCP/IP UDP/IP RS232 Optical	3G/4G/LTE Cellular WiFi ZigBee
general purpose SSs (Current, Voltage, Temperature, etc.)	IEEE 1815 IEEE 1815.1 IEEE 1451 ISO/IEC/IEEE 21451 ISO/IEC 30101	TCP/IP UDP/IP RS232 Optical	3G/4G/LTE Cellular WiFi WiMAX ZigBee 6LowPAN

3.2. Supervisory Control and Data Acquisition (SCADA)

The SCADA is an automation and control system based on computers and directly applicable to supervise SG systems. The supervisory control emerged to operate and control from a remote location. The control system is combined with data acquisition systems [40, 78]. The main functions of the SCADA are Monitoring, Data Presentation, Data Acquisition, Supervisory Control, Alarm display. It consists of both hardware and software monitoring levels. The main components of SCADA are Remote Terminal Units (RTU), Programmable Logic Controller (PLC), Telemetry system, Data Acquisition Server, Human Machine Interface (HMI). The computer gathers data and the signal is sent to the control unit. The Sensors are either analog or digital and are interfaced with the system. These are incapable of providing the dynamic state of the power system. The data received are also not time-synchronized. The information provided by SCADA is steady, low sampling density and asynchronous [96, 53]. The dynamic state of the system is not provided so that immediate action cannot be taken in case of failure. The Master Terminal Unit is the main part of the SCADA system which is the server, all the communications, data from RTU are managed and stored, while commands and interfacing with the operators are managed by the MTU.

Consider the diagram of the SCADA system depicted in Figure 5 which consists of several blocks, specifically, substation sensors (PLC, CTs, VTs, Temperature, Oil indicators, others) to RTU forward through a communication infrastructure, routed to the SCADA network to a specific application. Those applications include Open Platform Communications (OPC) Server, HMI Station, Supervisory system, SCADA Programming, Database, and Application Server.

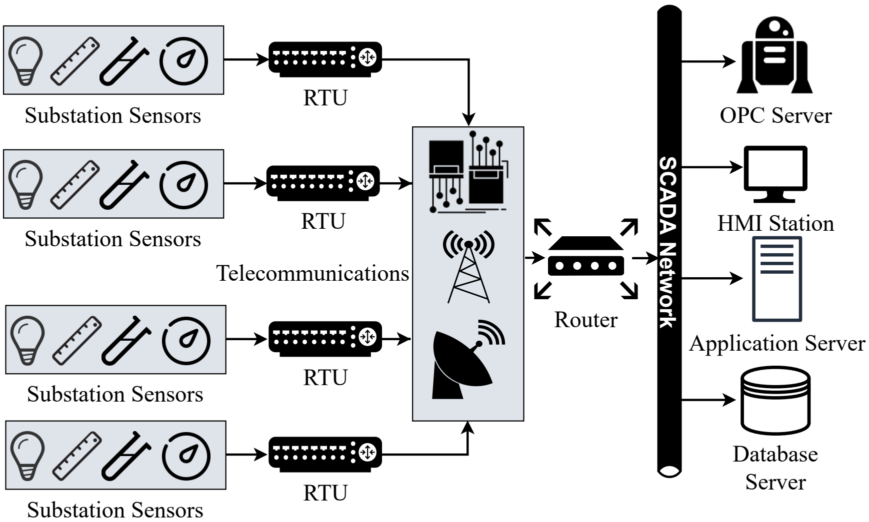

Figure 5: SCADA network architecture for SG systems.

3.3. *Synchronized Phasor Measurement System (SMPS)*

The Synchronized Phasor Measurement System (SMPS) was firstly developed in mid-1980's [97]. It measures the phasor of voltage, current, and the local frequency and its rate of changes. This SMPS consists of three main parts namely PMU, PDC, and Communication system. The PDC gathers the data from several PMU and rejects the bad data and aligns the timestamps [98].

Figure 6 illustrates the structure of a WAMS system including the PMU unit-specific components. PMU record measurements and time-stamps each measurement using the GPS. Data from individual PMUs is routed to a PDC that aggregates and time-aligns the data before passing it on to downstream application consumers. PDCs have expanded to provide additional data processing and storage functions [99]. An equivalent part of the power system is modeled based on the

PMU measurement. It is called the system identification and is an integral part of the Wide Area Monitoring and Control [100].

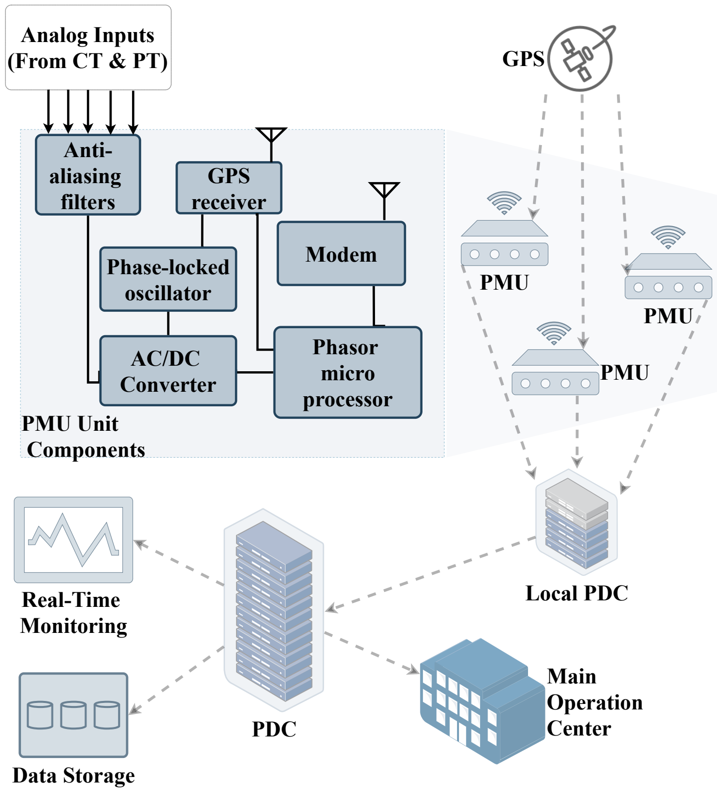

Figure 6: Example of a WAMS infrastructure including the PMU Unit components.

3.4. *Advanced Metering Infrastructure (AMI)*

AMI is a critical component that requires an understanding of the vision of SG. In general, AMI consists of the SMs and the Meter Data Management System (MDMS) [101]. Figure 7 represents AMI elements from an SM with a meter board and data tables transmitting data via a serial port through a communication board to a concentrator following by the MDMS to the application layer (*e.g.* DMS or/and Consumer Information System (CIS)) Sensing or perception acts as an essential process of interacting with the outer environment, throughout the current status of the system is denoted with quantified characteristics [102]. Each intelligent device takes up some computing power and has some self-sufficient capacities, distributing data and information that other devices cannot perceive.

The SMs consist of the communication board and the meter board that is connected normally using a serial port. The communication board handles the job of communicating with external nodes such as collectors or home devices for the accomplishment of the required computations. A set of tables in the main-board store critical information in the form of keys and passwords to establish secured communication. The power consumption measurements are also performed by the meter board. The communication board uses an interrupt based mechanism for obtaining

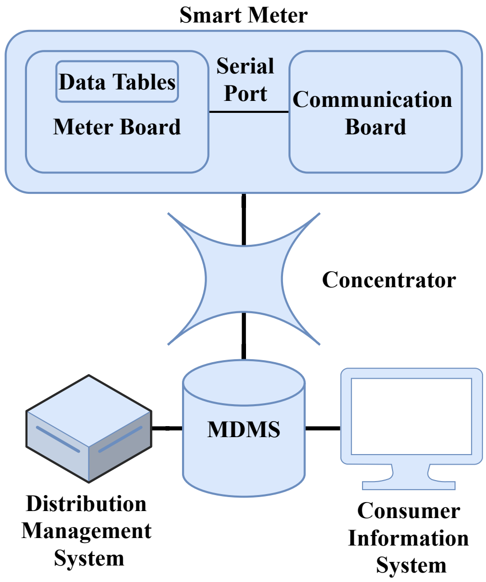

Figure 7: Advanced Metering Infrastructure (AMI).

data or other needed information from the meter board. The data is then finally sent to the utility by the communication board [103]. The MDMS is an essential component in AMI and serves as a database for long term data storage and management of events and data usage [40, 11, 104].

AMI also facilitates two-way communication between meter and distribution system operators. The two-way communication facilitates operations of many services for the distribution system operator that have been very hard to implement without smart metering attributes [103, 8]. For instance, a system operator detects faster a power outage without the interaction of the customer. Also, reporting the quality of the power delivered is another service provided by smart metering. SM also allows detailed monitoring of power flows within the distribution system that was previously available only at the substation/transmission level [105]. This particular monitoring enables utilities to respond promptly to fluctuations in consumption levels. The power flow monitoring information is also useful for real-time pricing, which is handled by one technology in a known as Demand Side Management (DSM). Recent advancements in SM technologies for systems have made several utilities and states to induce different time-based pricing initiatives[27, 106].

The presence of the SM throughout the world should double from 2017 to 2024, starting up new possibilities for customer-side control and analytics. Consequently, the combined global investment on AMI will roughly multiply over the same time, growing from $73 billion in 2017 to $145.8 billion in 2024 (all values USD) [107]. Table 4 summarizes the new AMI deployments announced on the world markets between April 2019 and September 2019. This counts a greater expansion over the Asian Pacific Region with over 13 million SM units.

According to [108] SM penetration in the United States (US) by 2020 will be over 90%, with an estimation of more than 85 million SMs installed. Table 5 shows the number of SM by city SG projects in the US published in OpenEI.org. Besides, Asia will be the largest market for smart meters over the next five years, considering almost two-thirds of the global AMI installed

Table 4: New AMI Deployments Announced, World Markets: April 2019 to September 2019 [107]

Region	Country	Stakeholder	Meters
Asia Pacific	Taiwan	Taipower	12,000,000
Asia Pacific	Pakistan	Lahore Electric Supply Company	1,200,000
Western Europe	Sweden	E.ON	1,000,000
Latin America	Uruguay	UTE	750,000
North America	US	City of Colorado Springs, Colorado	590,000
North America	US	Ohio Power	475,000
Middle East	Kuwait	Kuwait Ministry of Electricity and Water	300,000

base through 2024. China is the key market driver in the region. The country now ranks for more than half of all smart meters installed worldwide. The State Grid Corporation of China — the country's main power distribution and transmission utility — stationed 476 million smart meters between 2011 and 2017. India will emerge as an increasingly important player in the Asian market, thanks to the new installation of a centralized AMI procurement and financing process. As a result, India is forecasted to surpass Japan as the second-largest AMI market in Asia by as early as 2023.

3.4.1. AMI Technical Requirements

The capabilities of an AMI to support the simultaneous operation of major functions, including SM price-induced controls, Distribution Automation (DA), Demand Response (DR) and EV charging/discharging applications in terms of throughput and latency, have been analyzed in [109]. The numerical performance results from the selected communication technologies and protocols, summarized in Table 6, indicate that SG applications can operate simultaneously by piggybacking on an existing AMI infrastructure and still achieve their latency requirements. Table 6 offers a comparison of AMI communication technologies implementations among regions and countries. The predominant technology relies on different elements, such as existing metering infrastructure, Utilities prior communication protocols, communication fees, availability of Radio frequency (RF) spectrum, and environmental conditions, *e.g.* high density of buildings or distances to the back-haul network. Since different SG applications have different characteristics, including data size, data sampling frequency, latency and reliability requirements, it is paramount to ensure proper operation of all SG applications especially those sharing the same bandwidth with an AMI network.

3.4.2. AMI communication network security

The use of wireless communication in AMI leads to security issues in such systems. There are several security issues concerning AMI that needs attention, ranging from the consumer level to the generation as well as the producer level [42]. The adversary can launch an attack by sending false signals to meters that may lead to a power outage in a particular area as well as disturb the demand generation model. The adversary can also make use of the study of the utilization pattern of the consumers for devising new forms of attacks. Similar to other existing systems, AMI needs to adhere to the requirements of the security primitives of confidentiality, integrity, availability and non-repudiation [104].

AMI preserves confidentially by preventing any unauthorized access to the energy consumption pattern of consumers. Maintaining the integrity of the system through the detection of illegal

Table 5: US Smart Grid Projects including AMI according to OpenEI.org

Project	City	State	Smart Meters
ALLETE Inc., d/b/a Minnesota Power	Duluth	Minnesota	8,000
Baltimore Gas and Electric Company	Baltimore	Maryland	2,000,000
Black Hills Power, Inc.	Rapid City	South Dakota	69,000
Black Hills/Colorado Electric Utility Co.	Pueblo	Colorado	42,000
CenterPoint Energy	Houston	Texas	2,200,000
Central Maine Power Company	Augusta	Maine	600,000
Cheyenne Light, Fuel and Power Company	Cheyenne	Wyoming	39,102
City of Fulton, Missouri	Fulton	Missouri	5,000
City of Glendale Water and Power	Glendale	California	86,526
City of Quincy, FL	Quincy	Florida	56,000
City of Westerville, OH	Westerville	Ohio	13,000
Cleco Power LLC	Pineville	Louisiana	279,000
Cobb Electric Membership Corporation	Marietta	Georgia	190,000
Connecticut Municipal Electric Energy Cooperative	Norwich	Connecticut	22,000
Denton County Electric Cooperative d/b/a CoServ Electric	Corinth	Texas	140,000
Entergy New Orleans, Inc.	New Orleans	Louisiana	4,700
Lakeland Electric	Lakeland	Florida	124,000
Marblehead Municipal Light Department	Marblehead	Massachusetts	10,000
Navajo Tribal Utility Association	Ft. Defiance	Arizona	28,000
Pacific Northwest Generating Cooperative	Portland	Oregon	97,666
Reliant Energy Retail Services, LLC	Houston	Texas	140,000
Salt River Project	Tempe	Arizona	580,893
San Diego Gas and Electric Company	San Diego	California	1,400,000
Sioux Valley Southwestern Electric Cooperative, Inc.	Colman	South Dakota	29,000
South Kentucky Rural Electric Cooperative Corporation	Somerset	Kentucky	68,000
South Mississippi Electric Power Association (SMEPA)	Hattiesburg	Mississippi	225,757
Stanton County Public Power District	Stanton	Nebraska	2,315
Talquin Electric Cooperative, Inc.	Quincy	Florida	56,000
Tri State Electric Membership Corporation	McCaysville	Georgia	15,000
Wellsboro Electric Company	Wellsboro	Pennsylvania	4,589
Woodruff Electric	Forrest City	Arkansas	14,450

OpenEI.org is developed and maintained by the National Renewable Energy Laboratory with funding and support from the U.S. Department of Energy and a network of International Partners & Sponsors. Information updated on 28 January 2020.

Table 6: Predominant SM network Communication Technologies by Region

Region	Country	Technology		
		Mostly	$\Longleftrightarrow$	*Hardly*
Asia	China	PLC	RF Mesh	NB-IoT
	India	RF Mesh	-	-
Europe	Italy	PLC	-	-
	UK	Cellular	RF Point-to-Point	-
Latin America	Costa Rica	RF Mesh	-	-
	Uruguay	Cellular	WiMAX	-
North America	Canada	RF Mesh	PLC	WiMAX
	US	RF Mesh	PLC	WiMAX
Oceania	Australia	WiMAX	RF Mesh	RF Point-to-Point
	New Zealand	RF Mesh	RF Point-to-Point	-

data alternation. Availability requires the accessibility of data by an authorized user on demand [27, 110]. If the required data is not found at the time of need, the system violates the availability aspect of the security requirement of the system. Any natural or intentional incidents (such as hacking) must not hamper the system from operating correctly. For example, if the hacker wants to jam the network, the system must comply with the availability aspect. Accountability (non-repudiation) means an action that cannot be denied, i.e., the entities cannot deny the receiving or transmission of data. In the AMI network, a timely response to the command and control ensures accountability [104].

SG initiative brings the integration of intelligence information exchange among users, operators, and control devices. It demands a detailed examination and more systematic quantification of the human dynamics correlated with a multiple of cyber-attacks against many critical power system components [111]. Vulnerable cyber networks and growing cyber intrusion activities achieve many levels of consequences on power systems differing from the disclosure of confidential information to harmful large-scale outages [36, 70, 43]. Even before SG, multiple large outages have been caused primarily by events and failures associated with the processing and communication infrastructure [14].

3.5. Cyber-security in SG Monitoring

Since controlling and monitoring rely on the Internet Protocols (IPs) and general public solutions, the SG may be tempting to attackers as critical infrastructure. SG's critical interconnected nature delivers it as a target of cyber-terrorism. Hence, it is essential to extensively examine the components and identify subsisting vulnerabilities, and all possible cyber-security threats in the SG infrastructure [112]. All parts of SG system must ensure security. It means that the main security objectives have to be satisfied. The main security objectives are confidentiality, integrity, and availability (CIA triad). In the SG, the exact association of vulnerabilities and classes of cyber-security threats enables specifying proper countermeasures and counter cyber-attacks.

SG security concerns include data acquisition, and control devices such as PLC, SMs, IEDs, RTU, and PMUs. There are further network security difficulties, including firewalls, countermeasures, attack scenarios, encryption, intrusion analysis, routers, and forensic analysis. Due to security risks in common Information Technologys (ITs) background, we can assume that almost all aspects associated with ITs technology in SG applications have potential vulnerabilities.

Attacks on the electric grid resulting in infrastructural failures include cybersecurity breach, cascade failures, blackouts, etc. AMI is more vulnerable as it is central to the SG operation. The energy demand is ever-increasing worldwide and to effectively cater for the increased demands, existing generation, transmission, and distribution capacity require improved expansive integration and coordination for a secure and efficient supply. As a result, there is a need for adequately analyzing security issues in critical SG systems.

AMI architecture is more susceptible to cyber-attacks given the fact that it consists of a network of sensors, meters, devices, and computers for data recording and analysis. As a result, the SG security will have to cater but not limited to the AMI, Wide-Area Situational Awarenesss (WASAs), ITs Network integration, interoperability, DER, customer privacy, and efficiency. The attacks have majorly been targeted at AMI, especially the SM component, for electricity theft. AMI security requirements as it relates to the entire system, as well as its personnel and third parties' privacies, were developed by Advanced Security Acceleration Project – Smart Grid (ASAP – SG) and NIST led Cyber Security Coordination Task Group (CSCTG) [113]. SG commonly uses standard frameworks that provide comprehensive security measures considering different architectures.

Cyber-attacks are arguably the most discussed attacks over SG systems due to the vulnerabilities of the infrastructure to digital attacks. It is capable of leading the system to total collapse, if not properly guarded against. Any significant attack is capable of misleading the utilities in making wrong decisions about usage and capacity, as well as possibly blind them from impending problems or on-going attacks. Confidentiality, authentication, and privacy of critical data for grid reliability and efficiency must be guaranteed to prevent unauthorized modifications through the infrastructure. Therefore, Distributed cyber-security systems are designed to monitor the architecture in maintaining data integrity. [114] proposes a methodology called Smart Grid Security Classification (SGSC) developed for complex systems such as SG, centering on the specific aspects of the AMI metering infrastructure.

Cyber-attacks can hit the utility of a physical system, render them inoperable, hand over control of those systems to an outside entity, or endanger the privacy of employees and customer data. Most attacks regularly take one or a combination of four principal ***types of attacks*** [115]:

- A device attack aims to compromise and control a grid network device.
- A data attack endeavors to illegally insert, alter, or delete data or control commands in the communication network traffic to trick the SG to make wrong decisions/actions.
- A privacy attack intends to learn about a users' private or personal information by analyzing data from their SG network resources.
- A network availability attack principally takes place in the form of Denial of Services (DoSs). It intends to use up or flood the communication and computational resources of the network, failing or delaying the communication.

Among the cyber menaces on SG and SCADA systems, the false data injections attacks have attracted a great amount of research from the security and energy industries [116]. Based on cyber-physical channels, *e.g.*, eavesdropping, the attackers insert false data into smart meters to falsify the state of the power system, *e.g.* electricity theft. Although security protocols have been developed for SCADA systems, some important issues concerning false data injections attacks remain largely unresolved, such as intrusion into the control center at the cloud computing layer. The most common attack type at the physical layer concerning availability is jamming [112]. Jamming attacks occur mainly in wireless networks at the physical layer. Attackers only need to connect to the communication channel to perform a jamming attack. Table 7 depicts the type of attacks according to the level of network layer.

Table 7: Classification of SG Cyber-Attack types according to Network Layer [112]

Network Layer	**Attack Type**
Application Layer	CPU Exhausting, LDoS, HTTP Flooding, Protocol, Stack Buffer Overflow, Data Injection Attacks
Transport Layer	IP Spoofing, Packet Sniffing, Wormhole, Data Injection, Traffic Flooding, Buffer Flooding, Buffer Overflow, DoS/DDoS, MITM, Covert Attack, Replay Attack
MAC Layer	Traffic Analysis, Masquerading, ARP Spoofing, MITM, TSA, MAC DoS Attack, Flooding Attacks, Jamming Attack
Physical Layer	Eavesdropping, Smart Meter Tampering Attacks, TSA, Jamming Attacks

4. SG Communications infrastructure

The integration and interoperability of the conventional electricity grid with communication technologies present critical constraints for the evolving. The reformation of the power grid system was defined as part of the "Third Industrial Revolution" for energy [103, 117]. The legacy power system typically operates in a centralized manner with a radial topology, in which a group of consumers is fed from a single power source. This topology has very low reliability because any power failure or trip along the path will interrupt power delivery across the network [118, 119, 120]. Consequently, many utilities have resorted to a loop or hybrid network topology to provide alternate paths in the event of a fault. However, other prevailing factors such as an increasing global appetite for energy, frequent power outages, security issues, global demand to build an expansive structure, electricity theft, current evolution in information and communication technologies, serve as drivers for the modernization of the power grid [121]. Integration of Internet-of-thingss (IoTs) technology together with the power grid points to enhance the reliability of grids through continuous monitoring of component status, as well as environmental behaviors and consumer activities monitoring [4]. A huge amount of data related to monitoring and control transmitters across SG wireless communication infrastructures suffer from intensive interference and increasing competition over the limited and crowded radio spectrum considering the existing wireless networking standards [122].

The standard SG communication network architecture is composed by a three-layer hierarchical network, *i.e.* a Home Area Network (HAN), a Neighborhood Area N etwork (NAN), and a WAN. In the HAN layer, PLC and Zigbee technologies have been proven to be the best choices [123]. In the WAN layer, the optical network or even the WiMAX technology could be seen as a provisional solutions. Accordingly, most studies focus on NAN. This network plays an important role as a bridge of SG data communication between the HAN and WAN. This data network sustains connections between the demand side and supplies side to trade the electricity data from customers to suppliers to run many SG applications. Furthermore, NAN sometimes called the Field Area Network (FAN), also connects many electric devices in the transmission and distribution lines to perform monitoring, controlling, and protecting the power network. From this perspective, NAN is the most significant network layer in SG communication and demands more research efforts to build up a mature and reliable communication system for the smart cities context.

NAN/FAN applications require data transmission from a large number of terminal devices to a data concentrator/hub/substation or vice-versa. Consequently, these applications require communication technologies that support a higher data rate (100 kbps-10 Mbps) and larger coverage distance (up to 10 km). ZigBee mesh networks, WiFi mesh networks, PLC, as well as long-distance wired and wireless technologies, such as WiMAX, Cellular networks, Digital Subscriber Line (DSL) and Coaxial Cable are common technologies for NAN/FAN applications [124].

Networking Requirements for the SG network differ in various critical aspects from those Network Service Providers (NSP). NSPs are originally designed to support their customers' multimedia applications (including VoIP). While SG networks must support mission-critical applications such as SCADA, teleprotection, and synchrophasors that have significantly more stringent requirements on reliability, security, and performance. Consequently, the network design paradigm for the SG network differs substantially from the data network design practices used by NSPs.

With the emergence of the IoT and Machine-to-machine (M2M) communications, it is expected a massive growth in the sensor-node deployment. In general, IoT applications require Energy-Efficient (EE) and low-complexity nodes for a variety of uses in scalable wireless highly EE networks. Currently, sensing applications in the short-range environments use wireless technologies such as IEEE 802.11 wireless local area networks (WLAN), IEEE 802.15.1 Bluetooth, IEEE 802.15.3 ZigBee, Low-Rate Wireless Personal Area Networks (LR-WPAN), and others [125]. In contrast, long-range SG applications include wireless cellular standards, including 2G, 3G, 4G, and 5G technologies. Primarily, WLAN and Bluetooth were designed for high-speed data communication, whereas ZigBee and LR-WPAN were designed for wireless sensing applications in the local environments and are used for low data rate application for communication distances ranging from a few meters to a few hundred meters, depending on the Line of Sight (LoS), obstacles in the path, interference, maximal transmit power, etc. Wireless cellular networks such as 2G, 3G, and 4G are designed for voice and data communication, not primarily for wireless machine-type communication (MTC) applications, including sensing tasks. Although these technologies are used for sensing for one or other ways in some of the applications, their performance metrics in terms of reliability-performance-complexity trade-off in the wireless sensor networks may not be acceptable.

Figure 8 represents an integrated SG architecture view. A pictorial overview of the grid including clusters that form the generic SG landscape. Components of the grid are located in topological communities grouped into systems. The two dimensions of the SG plane are zones, representing the hierarchical levels of power system management: process, field, station, operation, and domains which cover the complete electrical energy conversion chain: generation, transmission, distribution, distributed energy resources, and customers premises. Communication feature belongs to another dimension; a dimension of five interoperability layers, including business, function, information, communication, and component layer. The communication layer interacts directly with each component in the grid. Within the communication infrastructure exist direct links (A, B, C, F, L, H) to specific applications into the component layer.

The WAN or FAN are often referred to as the backhaul. Backhaul networks (represented by the circles labeled L, C in Figure (8) can use wired or wireless technologies, enabling the aggregation and transportation of customer-related SG telemetry data, substations automation critical operations data, relevant DER, and micro-grid field data, and mobile workforce information. Neighborhood area networks (NANs) represented by circle B in the figure, integrates SMs and sensors nodes. The inter-substation network (F) carries revenue-generating data and critical protective relaying data. The backbone (H) is the network that interconnects all grid networks, providing a path for exchanging information.

Many of the communication applications are susceptible to single-point failures. Impacts of those communication failures degenerate system behavior, *e.g.* protection misoperation. Many proposals for a communication framework use existing architecture within the application of pair-to-pair, also relaying, among devices [126, 127], where all messages received by devices are acknowledged with a reply. There is no-correlation between communication links and fault indicator components, a measurement of total reliability [105]. A framework that provides continuous, reliable, secure and sustainable diversified SG communication represents a challenge for actual implementations. Deployment of SG components needs proper determination and implementation of a communication network satisfying the security standards of SG communication [101, 94]. The concept of using device-to-device communication or distributed solutions to compose and deliver services has been a favored trend for SG [128]. Assuredly, SG applications would benefit from next-generation device-to-device networks for service delivery, composition, enhancement, and analysis.

4.1. SG Communication Protocols

SG communications comprehend most modern communication technologies such as RF mesh, Power Line Communication (PLC), and/or ZigBee [37, 71, 110]. Nevertheless, each of these has its drawbacks. The RF mesh has low network capacity, high interference, and less coverage area. PLC suffers from low bandwidth, and the noise on the transmission line network affects the quality of the signal [10, 48]. Finally, ZigBee suffers from low processing capabilities, small memory size, and noise interference with WiFi, Bluetooth, and Microwave. Due to relatively low latency, large bandwidth, and high coverage throughout residential areas, the cellular networks have become a promising technology for the SG data network. Cellular networks primarily designed for Human-to-Human (H2H) communications may have an undergoing with the size and the type of data from SG devices. SG communication mainly considers M2M data communication without any human intervention [106].

A detailed list of the most relevant technologies used for the intercommunication within and between these domains can be found in Table 8 based on [1]. Various protocols exist for substation automation, including many proprietary protocols with custom communication links. Substation automation devices require interoperation from different vendors. As a notable mention, the IEC 61850 protocol family is specially adapted for the integration between grid sections.

Despite the aforementioned research, analyses of the importance of improving the security of the interdependencies in SG are a crucial factor to reduce cascade failures. Although more complex networks have been intensively studied for over a decade, the researchers still focus on the case of an isolated network without external interaction. Nevertheless, it is known that smart systems are building and working coordinate way; consequently, these systems must be designed as interdependent networks. The research on the interdependency problems will guide the development and application of new system ideas and design proposals towards the mitigation of the hazards posed by these interdependencies.

Table 8: SG Communication Protocols

SG Domain	Communication Media and Low Level Protocols
Last mile networks (FAN, NAN, AMI)	Wired: BPL (PLC), DLC (PLC), fibre, twisted pair, PDH, SONET/SDH, xDSL, POTS, PRIME (PLC), Meters&More (PLC), ANSI C12.18, ANSI C12.21. Wireless: radio frequency, microwave, cellular, GPRS, UMTS, LTE, IEEE 802.16 (WiMAX). Medium independent: TCP/IP suite, ANSI C12.22.
Backhaul Network	Wired: twisted pair, cable, fibre optic, POTS, SDH/SONET, PPP. Wireless: cellular, microwave, radio frequency, 3G, WIMAX, LTE. Medium independent: Frame Relay, ATM, MPLS, TCP/IP suite.
AMI networks	Wired: BPL (PLC), DLC (PLC), fibre, twisted pair, PDH, SONET/SDH, xDSL, POTS, PRIME (PLC), Meters&More (PLC), ANSI C12.18, ANSI C12.21. Wireless: radio frequency, microwave, cellular, GPRS, UMTS, LTE, IEEE 802.16 (WiMAX). Medium independent: TCP/IP suite, ANSI C12.22.
DER networks	Wired: serial, Ethernet, PPP. Wireless: radio, IEEE 802.15.4 ZigBee. Medium independent: TCP/IP suite.
Transmission grid	Wired: Serial Line, Ethernet, Frame Relay, PPP, ATM/TDM, BPL, DLC/PLC.
networks	Wireless: radio frequency, microwave, cellular, IEEE 802.16 (WiMAX). Medium independent: TCP/IP suite. IEC 61850 protocol family.
Link Layer/MPLS	Wired: Serial Line, xDSL, Ethernet, Frame Relay, PPP, ATM, TDM. Wireless: GPRS, Wi-Max, 2G, 3G, 4G, VSat, Wi-Fi, ZigBee. PLC: (Broadband Power Line, such as IEEE P1901 standard), DLC (Distribution Line Communications, such as PRIME), nb PLC (Narrowband PLC, such as Meters&More). MPLS: Multiprotocol Label Switching, it is "protocol agnostic" and commonly referred as layer 2.5.
Network Layer	Medium independent: IPv4, IPv6, IPsec.
Transport Layer	Medium independent: TCP, UDP, TLS/SSL.
Windmills	IEC 61850 protocol.
Hydro Power Plants	IEC 61850-7-410 protocol.
Other Systems	IEC 61850-7-420 protocol.

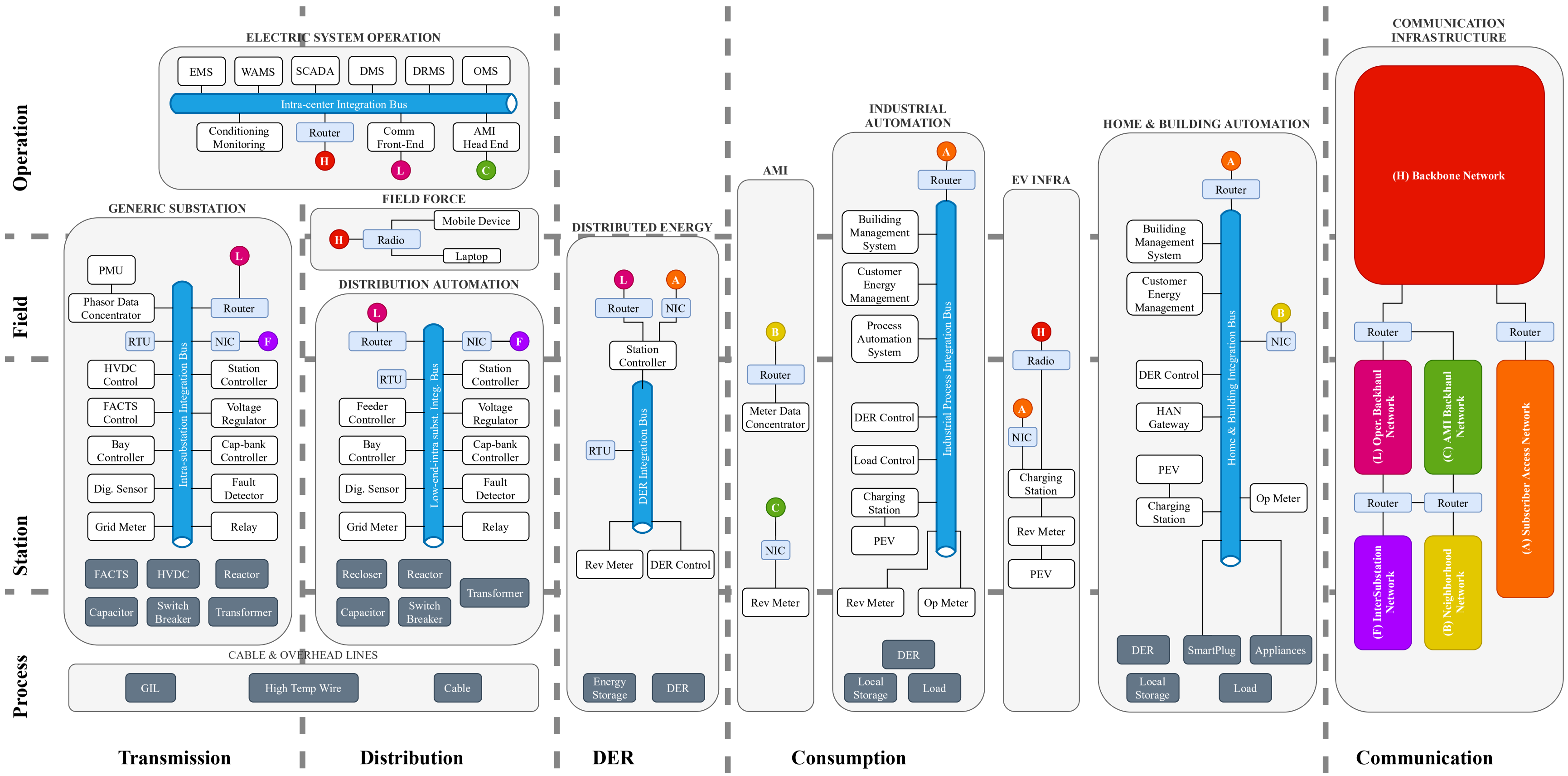

Figure 8: Smart Grid Architecture overview

The communication in SG systems should be distributed in a way that a failure of one device will not create a communications outage in a segment of the network. This can be accomplished with redundant communication devices that ensure that no device is connected only through one path.

An important application of IoT is the SG. The perception layer includes smart meters, network devices, and communication protocols. This layer collects information and sends it through a network layer comprising different classes of wired and wireless industry-specific or public communication networks. Within this topic, it is important to evaluate the performance of available access protocols for specific SG applications next to propose new protocols to achieve the next generations' network requirements.

The addition of modern protection functions is a difficulty in the emerging context of SG and may be achieved through the application of a compound of both existing and evolving technologies [70]. The latter must be designed to the real-time signal analysis and should be as computationally efficient as possible to be possible as a protective device function.

4.2. 5G technology enabling for SG

The fifth cellular generation (5G) technology is offering a significant advance in the combination of latency reduction and reliability enhancement. Following the beginning of 5G, electricity distribution has been one of the major use cases for Ultra-Reliable Low-Latency Communications (URLLC) [129]. 5G replacing optical communication links to achieve improved flexibility, reliability, and cost savings. Furthermore, 5G floors the way for wider integration of renewable energy sources to the electric power network. The mixture of low latency and high reliability makes 5G an option for replacing fixed connections. SG communication often has special performance requirements, especially very low latency ($\leq$ 1ms). The IEC 61850 standard defined the GOOSE protocol for transferring time-critical information, such as control commands and alarms, between IEDs with millisecond transfer delays [130].

URLLC is one of the three main 5G usage scenarios. In 3GPP, the first official release for 5G is Rel-15 completed in June 2018. The major use cases considered in Rel-15 are coming from industrial automation and electricity distribution. The 3GPP Service and System Aspects (SA) working group have been investigating various use cases, their requirements, and network architecture support for URLLC services. Moreover, the 3GPP Radio Access Network (RAN) working group has specified radio level standards that are within our focus area. In Rel-15, the system design target was set to achieve communication reliability corresponding to Block Error rate (BLER) of 10^{-5} for 32 bytes with a user plane latency of 1ms [129].

Currently, 3GPP is working on Rel-16 stage 3 (June 2020) and Rel-17 (early stages; expected to be available in June 2021). It also extends the supported services to cover time-sensitive communications (TSC), *e.g.* vertical industries' widely deployed Time-Sensitive Networks (TSN). The coveted target is to reach communication reliability corresponding to the BLER of 10^{-6} with sub-millisecond latency. Besides, further communication requirements must be considered, such as:

- Enhanced uplink configured grant transmission;
- Improved control channel reliability;
- Mini-slot repetition to achieve high reliability;

- Enhanced PDCP layer duplication;
- Intra/inter-UE multiplexing between different services;
- Enhance scheduling to support time-sensitive communications;
- Accurate time synchronization among involved network nodes within the same synchronization domain.

In this context, 5G technologies render a promising appeal for implementing the communication infrastructure that enables data traffic to be transmitted from measurement devices to control centers in WAMS. In fact, 5G is expected to meet the requirements for an SG implementation, with highly reliable communication, low latencies, strong security mechanisms to prevent malicious intrusion and high scalability [131].

Internet-of-things-Grid (IoTG) is a 5G communication solution developed based on Narrow-band Internet-of-Things (NB-IoT) and Enhanced Machine-Type Communication (eMTC), a dedicated industry spectrum for utilities in the VHF and UHF bands. IoT-G technology supports the aggregation of the fragmented narrowband spectrum to achieve broadband transmission capability [132, 133]. In addition, IoTG inherits the fundamental physical layer design parameters, including the frame length and subcarrier spacing from 3GPP NB-IoT and EMTC technology, while incorporating many 5G new radio (NR) technical features, including grant-free transmission-based protocol, self-contained frame structure, Code Block Group (CBG) transmission-based, and Integrated Access Backhaul (IAB) [132].

4.3. 5G technology for SG Teleprotection

Teleprotection signals from protective relays are crucial in PS. They support control power grid load and protect network equipment from severe harm. By allowing load-sharing, grid regulations and fast fault clearance, teleprotection guarantee continuous power supply. Protection requirements, hence, must be guaranteed urgent delivery when problems are detected, allowing faulty equipment disconnection before systemwide disaster occurs [134]. As utilities move from legacy synchronous digital hierarchy/synchronous optical network (SDH/SONET) communication networks to packet-based networks, however, the complexity in guaranteeing protection performance is intensified.

Utility communications networks have been SDH- and SONET-based [134]. That is evolving as legacy infrastructure and substation devices move to Ethernet transport and Internet Protocol (IP)/packet-based networks. The SG evolution is a key driver for this transformation because packet transport offers high capacity at a lower operating cost. This helps to handle traffic generated by advanced grid applications. Next-generation SCADA systems, wide-area situation awareness synchrophasor measurements and IP-based video surveillance are a few applications that demand the use of packet-switched networks [135]. Also, regulation in substation automation, such as the International Electrotechnical Commission (IEC) 61850 standard, require Ethernet capabilities throughout transmission and distribution.

Latency, or signal delay, requirements for utility networks diversify, but most line equipment can endure shortage or interruption faults of up to five power cycles. After that, the equipment might sustain resolute damage or the fault might affect other network parts. As a safety precaution, the actual operation time of protection systems is restricted to 70-80 milliseconds, including fault recognition, command transmission and line breaker switching time. Some system components, such as large electromechanical switches, are less sensitive and eat up most of the total time, leaving only a 10-milliseconds window for the communications element.

New IEC standards are even more stringent regarding protection messages. The backbone network domain is distinguished by the communicating endpoints in the high and extra-high voltage areas (i.e. primary substations). The diameter of the region to be reached is typically <1000km. The most important applications are protection functions (so-called Teleprotection, Differential Protection) which require ultra stable, reliable secure and real-time capable communication amongst the primary substations and towards the control center. Therefore these networks are today dedicated optical wireline networks. The specific requirements are:

- Bandwidth: in the range of Mbps to Gbps between the primary substations and towards the control center
- E2E Latency (upper bound): <5ms between the primary substations and towards the control center. IEC, "IEC 61850 Part 5: Communication requirements for functions and device models"
- Packet-loss: $< 10^{-9}$ (E2E Latency requirement has to be covered, as well as unacknowledged status information distribution (*e.g.* GOOSE-based) has to function properly, which is more demanding for high/extra-high voltage than for medium voltage applications).
- Availability: >99,999% equal to 5 min downtime p.a.
- Failure Convergence Time: Seamless failover required, i.e. no loss of information in case of a failure while keeping real-time delivery of the information (i.e. within a small number of milliseconds)
- Handling of crises (surviving long power down-times on a large scale, assuring black start capability): mandatory.

Compiling, SG services are often linked with rigorous requirements in terms of reliability, tolerating only short packet dropouts. Therefore, 5G has to include a wide range of diverse use case characteristics that are connected with a complex set of requirements as described above. To accommodate these under a common network topology, novel technology elements are demanded, as well as some disruptive techniques. The design of the new radio access network comprises the interaction among various communications interfaces that are seamlessly integrated and ends in a radical model shift on the connectivity theory in the future 5G vision. The efficient integration of the 5G access technologies introduces multi-connectivity approaches where the user equipment is simultaneously connected to several access technologies or frequency bands which could help to address the requirements in terms of crisis handling.

5. Detecting and Locating Faults

Protective devices automatically isolate a faulted area from the rest of the network when a short circuit fault occurs. Nevertheless, it is challenging to recognize the infringed sections of the network and the faulted parts. Existing methods consider algorithms that implement available information (i.e., data, measurements) to estimate the faults location or affected area. Fault location studies categorized into two main groups depending on the results and objective [8].

One group comprehends *outage area location methods*, which incorporates procedures using many available data sources such as customer outage calls or fault indicator signals to estimate the most probable affected area. The second group handles data and measurements to *locate the fault which caused the outage*. SG considers several fault diagnosis techniques, those techniques should include real-time estimation. In this context, Table 9 and 1 reviews works dealing with fault detection/location techniques; notice that a few of these researches include SG approach.

In this sense, Table 1 summarizes a selection of research surveys on fault detection/location techniques for SG systems. There are limited research works that provide models and comprehensively characterize faults in SG systems. In general, a systematic review has demonstrated that surveys and tutorials available in the literature report fault detection/locating in specific system applications, *e.g.* transmission, distribution, DG, EV, while several of them present comparisons in terms of requirements, advantages, and limitations. A summary of works dealing with fault detection/location in system-level applications is presented in Table 10.

Table 9: Description of related papers for Fault detection or location methods.

Reference	**One-phrase description**
[2]	Cluster-based learning approach for localized and classified faults
[46]	Combined wavelet and data-mining for fault detection and classification
[74]	Graph approach for secured fault detection and localization
[47]	A fault detection method of microgrids based on the PQ control strategy
[75]	Des-centralized protection scheme to improve transient stability using multi agent approach
[14]	A new approach for machine learning-based fault detection and classification
[76]	A Petri Net Approach to Fault Diagnosis and Restoration
[48]	Detection and location of high impedance faults utilizing PLC
[77]	Fault Detection, Identification, and Location with machine learning clustering algorithm
[30]	A multi-agent architecture to allow fault detections and dynamic recoveries
[31]	A maintenance scheduler framework of gearbox bearings from onshore wind turbines
[34]	Detects high impedance fault depending on the number of even harmonics in the voltage.
[78]	Disturbance Detection and Classification based on K-mean optimization
[49]	Fault detection and isolation for systems with unknown inputs
[79]	Fault localization using the phasor angles across the buses as a Gaussian Markov random field
[50]	Faults detection in changes in system matrices of the state space model
[80]	A framework for characterizing and managing the data generated by the synchrophasor
[51]	Voltage dips detection based on harmonic footprint
[35]	A wavelet multiresolution analysis technique for event detection and current pattern recognition
[52]	Fault detection and classification algorithm using cross-correlation coefficients
[36]	Detection of faults and attacks including false data injection attack in smart grid

Continued on next page

Table 9 – *Continued from previous page*

Reference	One-phrase description
[89]	Fault Detection, Isolation, and service Restoration algorithm using IEC 61850 based GOOSE tech
[37]	Injection of high frequency current signal to determine changes in the impedance characteristics
[53]	Fault diagnosis using the status of an intelligent electronic device and circuit breakers
[38]	Fault detection mechanism for wireless sensor networks based on credibility and cooperation
[54]	Fault location using voltage measurements from WAMS and the network bus admittance matrix
[55]	Fault detection and location of PV DC Microgrid Using Differential Protection Strategy
[81]	A wide-area fault-location scheme capable of detecting and identifying erroneous measurements
[56]	Fault detection method for voltage source converter based multi-terminal DC
[57]	Travelling-wave based method to detect, classify, and locate different dc fault types
[58]	Fault detection scheme for microgrid based on wavelet transform and deep neural networks
[82]	Fault monitoring system for detecting and classifying transmission lines faults
[59]	Fault detection and diagnosis of PV systems based on statistical monitoring approaches
[83]	A fault detection technique utilizing a phasor estimation to compute fault impedance
[60]	A fuzzy-based intelligent fault detection and classification
[32]	Fault detection and classification on convolutional sparse autoencoder
[61]	Fault detection algorithm for PV systems under the sequential change detection framework
[136]	Detection of Transients Induced by High-Impedance Faults
[62]	Travelling wave-based criteria for detecting such faults
[84]	Fault detection during power swings using the properties of fundamental frequency phasors
[39]	PV fault detection using fractional-order color relation classifier
[63]	Fault detection technique that analyzes the anomalies of faulty PV strings and arrays
[85]	PMU placement and fault detection algorithm to detect changes in the susceptance
[64]	Discrete wavelet transform (DWT) to detection of series arc faults in smart homes
[65]	A real-time discrete wavelet transform to detect the voltage transients generated
[66]	High-impedance fault detection based on nonlinear voltage–current characteristic
[40]	Integration of waveform analytics to improved situational awareness
[67]	Power line fault detection based on self-encoding neural network
[68]	Fault detection such as broken-rotor-bar and bearing faults
[69]	Fault detection algorithm based on multiresolution signal decomposition for feature extraction
[47]	Fault component characteristics of a microgrid under different impedance faults

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Table 9 – *Continued from previous page*

Reference	One-phrase description
[70]	Real-time detection scheme against false data injection attack
[86]	Islanding detection technique using the ANN classifier
[41]	Smart sensor to detect and quantify PQD
[42]	Real-time anomaly detection framework based upon smart meter data collected
[87]	Structure for the centralized detection of disturbances with noisy data and packet delay
[3]	Early detection of short-duration voltage anomalies from smart meters
[88]	Detection and classification of power quality disturbances
[71]	A correlation-based anomaly detection algorithm
[33]	A probabilistic framework to analyze large-scale real-time tweets to detect power outages
[72]	Algorithm for transmission line fault classification by using wavelet
[43]	Defensive techniques such as intrusion detection
[44]	Fault occurrence and location using optimal PMUs
[45]	Fault locating factors using a wavelet function
[73]	Fault-location method for use on highly branched networks

Table 10: Fault detection/location system-level of application

Level	References
Transmission	[9, 74, 75, 76, 77, 78, 79, 50, 80, 36, 53, 38, 54, 81, 56, 82, 83, 32, 62, 84, 85, 70, 41, 3, 72, 43, 44]
Distribution	[2, 46, 47, 48, 30, 34, 49, 51, 52, 36, 89, 37, 53, 38, 56, 57, 58, 60, 136, 39, 66, 40, 67, 47, 70, 86, 41, 42, 87, 3, 88, 71, 33, 43, 45, 73]
Comercial - Residential	[46, 35, 36, 55, 39, 64, 65, 70, 41, 33, 43]
DG	[47, 31, 49, 52, 36, 55, 56, 57, 58, 59, 60, 61, 39, 63, 65, 68, 69, 47, 70, 86, 41, 42, 87, 3, 88, 71, 43, 137, 138, 139, 140]
EV	[49, 56]

5.1. Non-Permanent Faults in Energy Distribution Networks

While the outage area location methods are employed to find the status of the protective devices and consequently the outage area, fault location methods aim to locate the *permanent faults* which caused the resulting outage. Fault location methods can also be applied to *non-permanent faults*. Approximately 75–90% of distribution network faults are temporary in nature [141]. Identification of their location provides the possibility of making remedial actions to avoid future sustained interruptions, and hence further improves the reliability by infrastructure enhancement. There are a wide variety of methods currently employed to locate transmission network faults. However, fault location in distribution networks faces new problems compared with SG arrival. Transmission lines are mostly equipped with dedicated protections, measurement devices, and fault locators. In contrast, distribution networks usually have laterals and load taps along their lines, which complicate the fault location procedure. According to [8, 42] some of the fault location problems and challenges in distribution networks are listed here:

- Geographic dispersion of distribution networks over a vast area;
- Existence of non-homogeneous lines;
- Presence of laterals, load taps and sometimes single and two-phase loads;
- Limited measurements, typically only available at substations;
- Dynamic topology of distribution networks;
- The effect of fault resistance which is usually non-negligible;
- Multiple fault location in distribution networks due to the presence of several branches.

The small-scale DER, such as microturbines, photovoltaics, wind turbines, fuel cells, and storage devices, are generally interfaced employing a voltage-sourced converter (VSC) due to their compliance in rendering controlled and high-quality power to loads and the grid. A challenging task in the protection of the inverter-interfaced islanded microgrids is to limit the fault current level; this degenerates the performance of traditional over-current protection schemes. Many fault detection strategies consider monitoring the VSC to establish fault characteristics [142].

5.2. Methods and Algorithms for Fault Detection-Location

To date, a plethora of research studies analyzed fault detection/location via either *impedance-based methods* or *computer simulations*, or even *numerical optimization* algorithms using an *analytical* or *learning*-based approach. In the following, different literature main algorithms are detailed and discussed. The discussions begin with the impedance-based methods which are the most developed class. Next, analytical methods have different requirements and algorithms. Finally, more recent learning-based fault detection/localization algorithms are discussed.

5.2.1. Impedance-based Methods

Methods for FD/L-SG based on impedance use steady-state measurements of currents and voltages during the fault to estimate an apparent impedance (or reactance) correlated with a distance to the fault. The main shortcoming of impedance-based methods is the miss-estimation due to the presence of many potential faulty points at the same distance. While all of the impedance-based fault location methods rely on the same fundamental concepts and assumptions, there are some features and differences which influence their performance and range of application. Impedance-based fault methods has been used extensively in the legacy power system; however, SG changing topology represents a challenge for the accuracy of such methods. [66, 34] are relevant works related to impedance-based methods. Both works applied a high impedance fault detection in distribution systems considering data from SMs. Waveforms measurements bring a trending topic to detect SG disturbances. Besides, those methods proved to be robust within non-linearities of the system for a wider number of system disturbances.

5.2.2. Analytical Methods

Analytical methods for FD/L-SG are generic processes combining the power of the scientific method with the use of a formal process to solve electrical fault problems among others. In fault detection, those methods are based on the system model by using knowledge of the system to create an analytical mathematical model. Many analytical methods implement a general-purpose estimation method for the particular detection process. The quality of fault detection depends mainly on two factors: the sophistication of the algorithm and the sampling rate of the system. Signal processing techniques represent an extended applied principal. Techniques as correlation, wavelet transform, and Fourier transform are effective techniques for fault detection. [66, 45, 3] show that those techniques achieve great accuracy with low-complexity techniques.

5.2.3. Learning-based Methods

Learning-based methods for FD/L-SG comprise computer algorithms based on Machine Learning (ML) principle that improve fault detection automatically through experience. Mainly described as ML processes, those algorithms formulate a mathematical model based on sample data, *i.e.* training data, to make forecasts or decisions without being explicitly programmed to do so. In this fault scenario, mathematical classification models that belong to supervised learning methods, are trained on the training set of a labeled dataset to accurately identify the redundancies, faults, and anomalous samples. Artificial Neural Networkss (ANNs) are amongst the most mature and widely deployed mathematical classification algorithms in fault detection and diagnosis [31, 51, 58, 67, 86, 41, 137, 138, 139, 140]. ANNss are easy to implement and well-known for their efficient self-learning capabilities of the complex associations, which inherently exist in fault detection and diagnosis problems. Another advantage of ANNss is that they perform automatic feature extraction by designating negligible weights to the irrelevant features, helping the system to avoid dealing with another feature extractor. Notwithstanding, ANNss tend to over-fit the training set, which raise consequences of having poor validation accuracy on the validation set. Henceforth, often, some regularization terms and prior knowledge are added to the ANNs model to avoid over-fitting and reach higher performance. Furthermore, properly determining the size of the hidden layer requires an exhaustive tuning parameterization to circumvent poor approximation and generalization capabilities.

The importance of computational intelligence to detect islanding phenomenon in smart distributed grids [137, 138, 139, 140]. Those works present a probabilistic Neural Network (NN) and Support Vector Machine (SVM) as powerful self-adapted machine learning techniques for fault detection. The authors analyze many islanding conditions with different active DG, load, capacitor or motor switching, external faults under several loading conditions, and DG participation.

Table 11 suggests the preference for Analytical or Learning-based algorithms over impedance-based methods for fault detection or location problems. Furthermore, the more recent from the aforementioned research works show that they are largely focused on the application of ANNs and MLs algorithms. Better results appear using mixed-schemes Analytical and learning-based; [70] successfully implement a Markov-chain-based analytical model and clustering classification technique. Also, according to Table 10, the system-level application marks a tendency on methods reliability. Therefore, legacy transmission and distribution systems still have a preference for impedance-based methods. But whether DG penetrations and other smart elements integrated into the network, learning-based became a powerful tool. Table 10 presents a summary of the system-level of application.

Table 11: Comparison of fault detection/location methods available in the literature

Impedance-based	Analytical		Learning-based	
[48, 34, 37, 83, 85, 65, 66, 47, 44]	*CORRELATION*	[3, 71, 52, 87]	*AI*	[53]
	DFT	[84]	*CLUSTERING*	[2, 78, 38]
	DWT	[64, 65]	*FUZZY*	[60, 69]
	FFT	[66, 68, 82]	*LEARNING*	[33]
	GRAPH	[74]	*ML*	[33, 14, 77]
	LOOKLIHOOD	[61, 62]	*MULTI-AGENT*	[75, 30]
	MA	[59]	*ANN*	[31, 51, 58, 67, 86, 41, 137, 138, 139, 140]
	MARKOV	[78, 79, 80, 70]	*PETRI-NET*	[76]
	MLE	[42]	*SPARSE AUTOENCODER*	[32]
	TRAVELING-WAVE	[73, 57]		
	UIO	[49]		
	VMD	[88]		
	WA	[40]		
	WT	[46, 35, 72, 45, 136]		

6. Future Research and Challenges in SG systems

The key elements to improve SG faults monitoring, detection, and location infrastructure are highlighted in this section. Notwithstanding the high number of proposals, the consolidation into one integrated tool that includes fault detection, classification, and location modules can be very challenging due to SG complex topologies. Furthermore, the emerging new sensing technologies and embedded computing present an opportunity to achieve QoS application requirements. Herein, we focus on the challenges related to the adaptation of legacy monitoring infrastructure, scalable communication architecture, cyber-security intrusion detection, real-time estimation, and handling a massive number of metering devices. The new panorama in future SG systems for smart city context may lie in the exploitation of ML techniques where heterogeneous energy systems interact with many other systems architecture at different application levels [28]. In the following, the main challenges need to be addressed in SG faults monitoring, detection, and location infrastructure are pointed out.

6.1. Legacy monitoring infrastructure

The worldwide electricity and energy sectors are looking to convert its century-old patchwork electricity infrastructure into a 21st century SG. The transformation would demand a phase-wise restructuring of the whole power system structure. The plan for the future FD/L-SG in the context of smart cities involves building on the existing infrastructure with new tools, techniques, and technologies such as distributed Artificial Intelligence (AI) and energy resources to increase the quality, efficiency, and security of existing systems while enabling the development of a robust architecture for the power grid.

To date, there is a large number of legacy data sources in the grid. Limitations to update those devices for AMI or PMU type have required backtrack compatibility to achieve SGs requirements. Servitization[1] and Industry 4.0 are considered two of the most recent trends transforming industrial companies. Servitization focuses on adding value to the customer (demand-pull) while Industry 4.0 is frequently related to adding value to the manufacturing process (technology-push). In the SGs context, solutions result in the development of low-cost retrofit or upgrade kits that allow integrating legacy equipment into the smart environment and thus enable digital servitization [143]. Smart sensors and/or edge gateways are aggregated to the SGs systems in the context of flexible and low-cost solutions from IoT sensors and smart-gateway to gather data, a package of sensors, and connectivity.

6.2. Scalable communication

SGs systems imply a large number of sensors deployed over a wide area for performing monitoring and control functions. Hence, a challenge in SGs is whereby to build a scalable communication architecture to handle the huge amount of data/information generated by that massive number of sensors. An SGs communication infrastructure requires to provide extensibility in terms of joining new devices and services into it, also improving the real-time monitoring of SM. SGs requirements should be constantly evaluated in terms of scalability and efficiency.

The lack of scalability and high installation cost are concern issues regarding wired communication technologies. Moreover, the wireless technologies would be preferred due to their high flexibility and scalability for wide-area communications. Though, to avoid adding more wireless access points and routers the mMTC section offers the scalability in wireless technologies without increasing the total installation costs of the network. Hence, appearing and effective big data technologies, such as data deep mining, stream data processing, data clustering, cloud computing, envelope analysis, and machine learning methods are crucial to pursuing the goal of scalability in SGs [144].

Ultimate SGs relies on the standardization of smart metering techniques to enable their continuous operation. Within 5G arrival, far-reaching activities are being performed in standardizing components and communication. Standardization forms an integral part of ensuring interworking and this factor needs more attention to make interoperability achievable for communication and information in SGs.

6.3. Cyber-security intrusion detection

SGs security concerns involve data acquisition, control devices, network security challenges, including firewalls, attack scenarios, countermeasures, encryption, intrusion analysis, forensic analysis, and routers. Analysis of cyber-attacks for considering significant factors of information security enables a well-organized and valuable way to give practical solutions for current and future attacks in SGs applications. Furthermore, due to the characteristics of smart grid applications, specific solutions need to be created for their private requirements.

ML approaches are used to determine, discover, and identify unauthorized use and injection of false data in networks, including SGs systems. Choosing the most efficient ML method(s) is related to their performance in cybersecurity datasets. Hence, we conclude that further research

[1] In the emerging servitization-centered economy, companies are shifting from selling products to selling access to and the outcome those products deliver, redefining the way the manufacturers do business.

is required to provide a comparative study of ML methods for cyber-security intrusion detection in SGs systems. Furthermore, the best-suited ML method may be different for different types of scenarios. Thus, the comparative study must comprise a rich collection of systems, types of attacks, and scenarios. Future research should evaluate auditing performance to detect any compromised device where a high number of devices in an IoT based SGs. How strict access control and authentication methods affect multiple access performance in a massive device scenario.

Additionally, the primary concerns in the detection of cyber threats are computational efficiency and minimizing the rate of false positives. Hence, future applications should increase the computational speed of security algorithms while preserving a high detection accuracy and a low rate of false alarms. Another research hollow is the mitigation of cyber threats that have already infected a smart grid. Against the existing background, detection, and prevention of cyber threats focus on mitigating those threats. Therefore, future trends in this field of study are projected towards the mitigation of cyber threats as well as robust deep learning algorithms for efficient detection of cyber threats.

6.4. Real-time estimation

Fundamental aspects of future smart cities are SM and AMI. Its comprehensive enactment leads to a significant impact on the efficient functioning of smart cities. Impact related to unlimited savings and/or greater ease of use for consumers at all income levels and suppliers of utilities, by providing real-time data collection and user consumption patterns. The development of smart cities depends on the wireless network standards, which must assure attending utility demands at lower costs, more bandwidth, and quality of service. Moreover, infra-structure legacy related to the wireless network and existing IoT concepts and implementation are fundamental to achieve a fully interconnected city. Future works focus on the role of real-time monitoring in smart cities.

Real-time estimation should consider forecasting schemes into distribution networks, taking into account for dynamically changing environments, and corresponding time dependencies [145]. The SGs scenarios imply a bunch of data processing that requires efficient low-complexity and high-performance signal processing algorithms. A real-time estimator should be both flexible and effective, providing an accurate evaluation of the SGs state under a wide variety of operation conditions, from fault to normal operation scenarios [146].

6.5. Massive-congested AMI deployments

Beyond the quality and computational requirement of handling data, the overarching concerns of handling data emanating from numerous IoT devices will likewise have to be investigated profundity. Random Access (RA) protocols for massive SGs communication devices and system performance stand for trending research. The influence of RA protocols in achieving QoS SGs requirements encourages future research works brought out in this area. It is paramount establish the role of RA in accomplishing the QoS requirements and point out the contrasts between traditional electrical systems and SGs QoS requirements.

RA congestion occurs when a massive number of devices transmit data at the same time with the same clock synchronization. This issue causes a collision that drives to a negative impact on a cellular network's performance in terms of packet losses, energy consumption, and longer delay [147]. Moreover, the trend of M2M device connections is larger than mobile phone users. One of the key roles of SGs devices is to broadcast data in a periodic time. Due to the limited number of preamble signatures, a huge number of M2M devices accessing the network will result in the recycling of the same preambles causing a preamble conflict issue [7]. For instance, in LTE networks with the Random Access Channel (RACH), all devices can establish connections with an eNode-B without centralized control [148]. Although devices (eg. SMs) communication handles the regular time to access a network. This is the worst-case scenario concerning preamble signatures, even if some are kept for specific devices.

7. Conclusions

The fundamental notion of a more efficient, data-dependent, and consumer-centered counterpart of the conventional power grid constitutes the Smart Grid concept. Smart devices with processing, storage, and communication capabilities integrating the power grid to become the IoE or IoTG. IoE has the potential to transform various aspects of the legacy power system and our lives as an interconnected smart society. Unlike the traditional power grid with limited information for fault diagnosis, the SGs can derive actions from many sources of information and improve many aspects of the system.

In this work, in total, more than 150 papers published in high-impact journals from 2015 to 2020 have been extensively reported observing the evolution of FD/L-SG techniques, methods, and systems. More specifically, 60% of cited journal-papers have been published in high JCR impact factor journals (IF> 3.0), while 12% of citations come from relevant conference papers. Over 76% of cited papers from 2015 or newer and 40% published in 2018 or newer. This extensive literature review revealed a tendency of the application of machine learning-based tools in undertaking several FD/L problems and offered the scope of future development of promising subjects with the appliance of the monitoring network. Notwithstanding, the quick expansion in the use of learning-based (ML tools) prevails and worth further research effort. Moreover, the high-performance data processing, and analysis for intelligent decision-making of large-scale complex multi-energy systems, lightweight machine learning-based solutions in the IoE. This survey also highlighted the lack of efficient underlying computing and communication technologies, *e.g.*, edge computing and the future 5G wireless networks, for advanced applications in the SGs systems.

Furthermore, this survey discussed the current trends and new perspectives in SGs faults scenarios through the understanding of the monitoring infrastructure, the communication infrastructure, and the advances detection and location techniques, with a particular focus on the identification of the trending research topics. In addition, the survey offers a comprehensive point-of-view to researchers, academicians, and professionals interested in exploring relations between SGs monitoring and the FD/L techniques. Finally, it provided a framework for the additional exploration and expansion of knowledge and insights of SGs monitoring and the FD/L techniques.

Appendix A. SG Research Classification

Table A.12: Relevant Publications inside the scope of SG systems

Publication	**Scope**							
	Fault	*Det.*	*Loc.*	*Monitor.*	***SG***	*μ-grid*	*DG*	***Comm***
Milioudis et al. (2015) [48]	✓	✓	✓		✓			✓
Bush (2014) [117]	✓				✓			✓
Jiang et al. (2014) [77]	✓	✓	✓		✓			
Andresen et al. (2018) [11]	✓	✓		✓	✓			
Ben Meskina et al. (2014) [30]	✓	✓		✓	✓		✓	
Bangalore and Tjernberg (2015) [31]	✓	✓			✓		✓	
Chakraborty and Das (2018) [34]	✓	✓			✓			
Gharavi and Hu (2018) [78]	✓	✓			✓			
Haes Alhelou et al. (2018) [49]	✓	✓			✓			
He and Zhang (2011) [74]	✓	✓			✓			
He and Zhang (2010) [79]	✓	✓			✓			
He and Blum (2011) [50]	✓	✓			✓			
Jiang et al. (2016) [80]	✓	✓			✓			
Katic and Stanisavljevic (2018) [51]	✓	✓			✓			
Koziy et al. (2013) [35]	✓	✓			✓	✓		
Mahfouz and El-Sayed (2016) [52]	✓	✓			✓		✓	
Manandhar et al. (2014) [36]	✓	✓			✓			
Parikh et al. (2013) [89]	✓	✓			✓		✓	
Pasdar et al. (2013) [37]	✓	✓			✓			
Rawat et al. (2016) [53]	✓	✓			✓			
Shao et al. (2017) [38]	✓	✓			✓		✓	
Devi et al. (2018) [44]	✓		✓		✓			
Dhend and Chile (2017) [45]	✓		✓		✓			
Farughian et al. (2018) [13]	✓		✓		✓			
Robson et al. (2014) [73]	✓		✓		✓			
Ferreira and Barros (2018) [96]	✓			✓	✓	✓		
Jiang et al. (2018) [102]	✓			✓	✓			
De Santis et al. (2015) [149]	✓				✓			
De Santis et al. (2018) [2]	✓				✓			
Dhend and Chile (2018) [106]	✓				✓			
Gopakumar et al. (2015) [150]	✓				✓			
Hare et al. (2016) [16]	✓				✓	✓		
Jiang et al. (2018) [76]	✓				✓		✓	
Kazemi and Lehtonen (2013) [151]	✓				✓			
Kordestani and Saif (2017) [152]	✓				✓			
Ntalampiras (2016) [118]	✓				✓			
Sayed et al. (2017) [153]	✓				✓			
Xu et al. (2012) [154]	✓				✓			
Rahman et al. (2018) [127]	✓							✓
Tarhuni et al. (2015) [105]	✓							✓
Das et al. (2017) [54]	✓	✓	✓					
Dhar et al. (2018) [55]	✓	✓	✓			✓		
Dobakhshari and Ranjbar (2015) [81]	✓	✓	✓					

Continued on next page

Table A.12 – *Continued from previous page*

Publication	**Scope**							
	Fault	*Det.*	*Loc.*	*Monitor.*	***SG***	*μ-SG*	*DG*	***Comm***
Li et al. (2018) [56]	✓	✓	✓					
Saleh et al. (2017) [57]	✓	✓	✓			✓		
Yu et al. (2017) [58]	✓	✓	✓			✓		
Gopakumar et al. (2018) [82]	✓	✓		✓				
Harrou et al. (2018) [59]	✓	✓		✓				
Sadeghkhani et al. (2016) [142]	✓	✓		✓		✓	✓	
Affijulla and Tripathy (2018) [83]	✓	✓					✓	
Babaei et al. (2018) [12]	✓	✓						
Chaitanya and Yadav (2018) [60]	✓	✓					✓	
Chen et al. (2016) [32]	✓	✓						
Chen et al. (2016) [61]	✓	✓					✓	
Costa et al. (2015) [136]	✓	✓						
Daryalal and Sarlak (2017) [62]	✓	✓						
Hashemi et al. (2017) [84]	✓	✓						
Kuo et al. (2017) [39]	✓	✓				✓		
Madeti and Singh (2017) [10]	✓	✓						
Madeti and Singh (2017) [63]	✓	✓						
Nagananda et al. (2015) [85]	✓	✓						
Qi et al. (2017) [64]	✓	✓						
Saleh et al. (2017) [65]	✓	✓						
Tokel et al. (2018) [14]	✓	✓						
Wang et al. (2018) [66]	✓	✓						
Wischkaemper et al. (2015) [40]	✓	✓						
Xi et al. (2017) [67]	✓	✓						
Yang et al. (2016) [68]	✓	✓						
Yi and Etemadi (2017) [69]	✓	✓					✓	
Zhang and Mu (2018) [47]	✓	✓				✓	✓	
Bahmanyar et al. (2017) [8]	✓		✓				✓	
Mishra et al. (2014) [72]	✓		✓					
Elkalashy et al. (2016) [155]	✓						✓	
Ferreira et al. (2016) [9]	✓							
Mar et al. (2019) [156]	✓							
Negari and Xu (2017) [157]	✓							
Prasad et al. (2018) [158]	✓							
P. et al. (2018) [159]	✓							
Wasekar et al. (2017) [160]	✓					✓		
Wu et al. (2017) [120]	✓							
Al Ridhawi et al. (2020) [128]					✓			✓
Calderaro et al. (2011) [126]					✓			✓
Depuru et al. (2011) [101]					✓			✓
Emmanuel and Rayudu (2016) [103]					✓			✓
Gao et al. (2012) [110]					✓			✓
Jaradat et al. (2015) [4]					✓			✓
Karupongsiri et al. (2017) [147]					✓			✓
Honggang Wang et al. (2013) [122]					✓			✓
Yang et al. (2018) [94]					✓			✓

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Table A.12 – *Continued from previous page*

Publication	Scope							
	Fault	*Det.*	*Loc.*	*Monitor.*	***SG***	*μ-SG*	*DG*	***Comm***
Phan and Chen (2017) [27]		✓		✓	✓			
Huang et al. (2016) [70]		✓			✓			
Kumar and Bhowmik (2018) [86]		✓			✓			
Martinez-Figueroa et al. (2017) [41]		✓			✓			
Moghaddass and Wang (2018) [42]		✓			✓			
Ahmadipour et al. (2019) [139]		✓			✓	✓	✓	
Seyedi et al. (2017) [87]		✓			✓	✓	✓	
Wan Yen et al. (2019) [3]		✓			✓			
Zhang et al. (2013) [43]			✓		✓			
Anandan et al. (2019) [95]				✓	✓			
Honarmand et al. (2019) [90]				✓	✓			
Madueno et al. (2016) [148]				✓	✓			
Munshi and Mohamed (2017) [29]				✓	✓			
Seyedi et al. (2017) [93]				✓	✓	✓	✓	
Artale et al. (2017) [26]					✓		✓	
Cosovic et al. (2017) [5]					✓		✓	
Di Santo et al. (2015) [161]					✓			
Dileep (2020) [17]					✓			
Fadul et al. (2014) [119]					✓			
Guarracino et al. (2012) [121]					✓		✓	
Howell et al. (2017) [162]					✓		✓	
Liboni et al. (2016) [163]					✓			
Mahmoud and Xia (2019) [104]					✓			
Rahman et al. (2015) [75]					✓			
Saleem et al. (2019) [6]					✓			
Seyedi and Karimi (2018) [164]					✓		✓	
Tuballa and Abundo (2016) [165]					✓			
Wallace et al. (2016) [99]					✓			
Zhang et al. (2013) [98]					✓			
Zúñiga et al. (2020) [166]					✓			
Bockelmann et al. (2018) [7]								✓
Achlerkar et al. (2018) [88]		✓					✓	
Chen et al. (2015) [71]		✓					✓	
Ahmadipour et al. (2018) [137]		✓					✓	
Ahmadipour et al. (2018) [138]		✓					✓	
Ahmadipour et al. (2019) [140]		✓					✓	
Sun et al. (2016) [33]		✓						
Thanos et al. (2017) [167]				✓		✓		
Xiang et al. (2018) [111]				✓				
Mahela and Shaik (2016) [168]							✓	
Mishra et al. (2016) [46]						✓		
Monadi et al. (2017) [169]						✓		
Nguyen et al. (2013) [170]								
Pertl et al. (2018) [100]							✓	

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