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Control Networks and Smart Grid Teleprotection: Key Aspects, Technologies, Protocols, and Case-Studies

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ABSTRACT The appeal for more reliable, efficient and resilient power grids has become indispensable with the recent technological development and ever-increasing demand for electrical energy. These goals might be achieved by introducing sensors and actuators in the power grid, with the purpose of enabling a smart control of the power network. All power devices must be connected using a reliable communication network, which should be able to operate even when the power grid fails. Currently, several communication technologies have been applied for supporting this new application scenario. This article aims for reviewing both academic and market use cases for technologies applied to the mission-critical, control networks and Smart Grid applications, such as teleprotection, self-healing, communication with control centers and field devices, among others. More specifically, the key aspects, potential technologies, main protocols and use cases of operating data networks in energy transmission, power distribution and smart grid environments, including circuit and packet switching technologies, are discussed into details. Furthermore, resilience and the main telecommunications technologies used in power grids, as well, the correlation among them, are exploited in practical point of view. The article provides a broad discussion on the best telecommunication options to build the emerging intelligent energy distribution systems, covering control networks, teleprotection, and smart grid applications.

INDEX TERMS Power grids, telecommunications, power system protection, smart grids, packet switching, circuit and systems, optical fiber networks, SCADA systems, wireless networks, distributed control.

I. INTRODUCTION

The power grid designed to supply energy for all sectors of modern society started to be deployed 100 years ago and has been constantly evolved during this time frame, providing consumers with large-scale power [1]. Over these years, the world scenario has changed significantly. Technologies have evolved, new devices have been created and a significant demographic increase has made energy demand ever higher. Even with increasing demand, power grids have not matured enough to meet these challenges and, consequently, will probably face several problems in the upcoming years, such as the interconnection of distribution grids with power generated by plants from alternative sources and the energy

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generated by the customers; monitoring of energy supply to avoid peak demands, adapting power generation to the arrival of electric vehicles, among other sources [2].

To adapt the power grid for future needs, the current solution must advance to deal with several upcoming challenges. Future power grids must be more reliable for day-to-day operations, providing higher security against attacks and failures [3]–[5], increasing the agility to adapt itself for different demands [6]–[8] and providing greater sustainability through the use of renewable energy sources [9]–[11]. This evolutionary view of today's energy grids is called Smart Grids, which employs telecommunication and computing technologies to form a two-way information channel among customers, producers and utilities, in order to solve the energy sector emerging problems.

The path of modernization and development is paved by energy consumption. Modern lifestyle is based on a high level of power consumption and there is a clear pattern showing that this consumption will considerably increase in all sectors during the next years. Given this scenario, the incorrect operation of a protection device can lead to the interruption of large power blocks and cascading shutdowns, causing major damage to the network, resulting in fines for the operator, limitation of essential services, and economic losses like the interruption of working hours and losses for consumers [12].

Given this situation, several initiatives have been taken by utilities in the topic of power grid automation, leading to a growing demand for communication services to foster these automation processes. This work is regarding the demand for communication technologies in smart grid applications, with special attention to mission-critical services, such as teleprotection, self-healing, and communication with control centers and field devices. Most of the communication solutions employed today in smart grid communication are based on static scheduling for data transmission, using synchronous networking schemes, like Time Division Multiplexing (TDM). However, the dynamic and flexible grid configuration and the fast response for mission-critical legacy systems will demand agility that is not supported by this approach. Hence, this survey will focus on solutions that could be used to migrate the energy control networks from the current static approach to modern flexible, programmable, and self-organizing solutions. In this context, the main contributions of this work are the following:

- An innovative and comprehensive deep review of established and novel telecommunication technologies for smart grids and teleprotection, self-healing, and communication with control centers and field devices in energy distribution networks.
- The work covers migration from static/legacy energy control networks to flexible/programmable smart grid solutions, covering fast response for mission-critical legacy systems, as well as flexible and elastic connectivity, e.g. Fiber-Wireless (Fi -Wi) networks [13]–[15] and 5th Generation Mobile Networks (5G) [16], [17].
- Legacy and IP-based technology applied for communication in the smart grid context are surveyed and compared. Novel IP-based technologies, like Software-Defined Networking (SDN) [18], Cloud-Radio Access Networks (C-RAN) [19], 5G, and Internet of Things (IoT) [20] are explored in the context of teleprotection, self-healing, and control of energy distribution networks.
- Post-IP architectures — the so called Future Internet Architectures (FIAs) [21]–[26] are also briefly covered, as well as their benefits for mission critical energy networks.

The remainder of this article is organized as follows. Section II presents the related works regarding communication solutions for the smart grid. Section III shows the panorama of technologies and their geographical domains in the smart energy scope. Section IV reports some applications applied in smart grid scenarios. Section V discusses resilience in power grids, while telecommunications technologies for control networks are presented in Section VI. In Section VII, a correlation is made between telecommunications technologies and mission-critical techniques in power grids. Finally, Section VIII presents the main conclusions of this survey.

II. RELATED WORKS AND SURVEYS

In this survey, the main wired and wireless technologies employed in the smart grid and mission-critical scenarios are discussed, mainly focusing on their application for energy transmission and distribution. Other works that carried out a complete or partial survey of the wired and wireless technologies used in smart grid scenarios and their applications can be found in [27]–[41]. The main wireless technologies employed in smart grid scenarios are presented in [10], [42], [43]. In [44], Meng *et al.* described the main wireless communication technologies employed in Neighborhood Area Networks (NANs). This study also contributes to addressing networking topologies, routing algorithms, and security requirements for the deployment of smart grids in the NAN domain. In [45], Saputro *et al.* performed a survey of the main studies related to smart grid routing scenarios. The advantages and disadvantages of each routing protocol were evaluated according to their application area.

Several papers in the literature addressed specific applications in smart grids. In [46], Šastný *et al.* performed a survey of the main technologies and protocols employed in the application of Smart Metering (SM). The advantages, disadvantages, and characteristics of technologies, such as Worldwide Interoperability for Microwave Access (WiMAX), Wireless Fidelity (WiFi), General Packet Radio Services (GPRS), and ZigBee are analyzed when employed for SM applications. In [47], a review of the wireless technologies employed in advanced metering infrastructures is presented. Technologies like Zigbee, Long Range (LoRa), Bluetooth, SigFox, among others, have been evaluated. As additional contributions, the authors provided detailed insight into the use of smart meters in the smart grid scenario, evaluation of routing protocols, and open issues regarding the SM applications. In [48], an evaluation of the communication technologies employed to communicate with renewable resource networks has been described. The authors presented the communication systems employed in some real projects, as well as open questions for communication networks applied for renewable energy resources. In [49], Ramírez and Céspedes surveyed the key communication technologies and routing protocols applied in NAN for Advanced Metering Infrastructure (AMI). The performance requirements for AMI has been provided, as well as an assessment of routing protocols and networking technologies. Finally, open issues on wired and wireless for the NAN domain have been discussed.

Despite not being the focus of this work, the advancement in big data and machine learning has enabled energy utilities to have the ability to evaluate data from smart meters, network supervisory systems, interruption management systems, devices located in the field, among others. Through this process, they will be able to learn from this data, adapting the characteristics of the users and programming themselves for possible events that may occur in the energy networks. An overview of these techniques usage in the smart grid scenario can be seen in references [50]–[58]. In [59]–[62], works related to the Big data in the preventive maintenance of equipment present in the power networks are presented. In [63]–[66], studies that evaluated machine learning techniques to assist in the optimization of energy consumption have been presented.

Concerning the works mentioned above, the main contributions of this survey include a deep update focusing on smart grids and mission-critical topics, delving into aspects related to communication technologies employed to enable the applications demanded by these scenarios. A correlation among communication technologies and smart grid mission-critical applications is provided, as well as an argument regarding the migration from legacy deterministic to statistical communication systems.

III. OVERVIEW OF TECHNOLOGIES AND THEIR GEOGRAPHIC DOMAINS

Telecommunications networks can be classified according to their area of coverage and the data rate required to support specific applications and services. Hence, operating networks can be divided into Home Area Network (HAN) [67], Building Area Network (BAN) [68], Industrial Area Network (IAN) [69], NAN [70], Field Area Network (FAN) [70], Wide Area Network (WAN) [67] and Radio Access Networks (RANs). The main requirements for each one of these networks are presented in Figure 1.

HAN, BAN, and IAN are directly linked to the end consumer. These networks are deployed indoor and require short-range and low communication rates. They use technologies that offer a communication rate of up to 100 kbps and cover a distance of approximately 100 m [34]. HANs are client-domain private networks (home networks) that can be used to manage home energy, as well as home automation [71]. BANs are networks for buildings, in which multiple HANs are grouped. Applications related to energy management and building automation must be supported by these communication networks [72]. IANs are networks focused on industrial implementations that incorporate sensors, controllers, and management software [73].

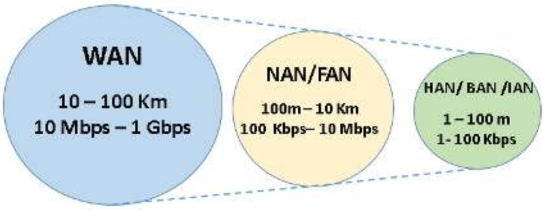

FIGURE 1. Coverage area and data rate required for HAN, BAN, IAN, NAN, FAN and WAN.

NANs are employed in the power distribution industry and are responsible for communicating smart grid measurements, enabling the interconnection of HAN, BAN, and IAN with WANs of the power utilities [74]. FANs allow connecting smart devices to the operating network and substations, as well as connecting devices such as line monitors, power supplies, circuit breaker controllers, capacitor bank controllers, transformers, reclosers, and other devices. These devices are used for fault detection in operating networks and system automation to ensure greater reliability and Quality of Service (QoS) [75]. With a large number of devices and the need for a wide coverage area on the NAN and FAN networks, communication technologies should provide transmission rates around 100 kbps and 10 Mbps and provide coverage of up to 10 km.

There are two types of WANs, named as backhaul and core networks [45]. Backhaul networks are responsible for connecting the NAN to the core network, while the core network itself connects the utility metropolitan networks and substations. The WAN needs to cover a large geographical area and can reach thousands of kilometers (10 km to 1000 km). This network needs high data rates and can reach Gbps (10 Mbps to 1 Gbps) [34]. To reach the required high data rates and cover long distances, the RANs must take advantage of emerging technologies from both optical and wireless communications systems. In this way, Cloud/centralized RAN (C-RAN) has been considered as the main architecture for composing futures mobile communications physical layer. Figure 2 shows the concept of C-RAN architectures, in which the centralization of the Baseband Units (BBUs) and some network functions are concentrated in the Central Office (CO), aiming to share computational resources and storage in accordance to the cloud computing design principle [19].

IV. SMART GRID APPLICATIONS

The increase in electricity consumption due to economic growth and the increase in equipment connected to power networks is mostly served by concessionaires and in the minority, by consumers themselves through their local generation

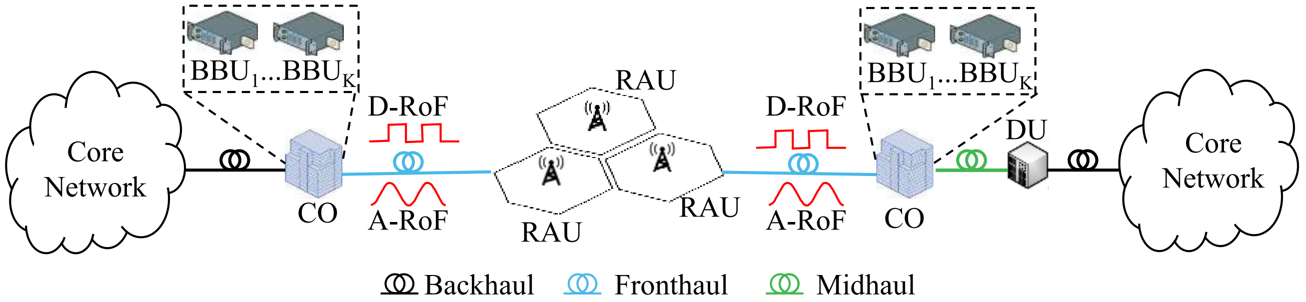

FIGURE 2. C-RAN architecture: BBU - baseband unit; CO - central office; D-RoF - digital radio over fiber; A-RoF - analog radio over fiber; RAU - remote antenna unit; DU - distribution unit.

or storage systems [76]. In this context, electric vehicles are included, which are increasingly present, being both suppliers and consumers of energy. While these loads help to solve environmental problems by reducing the emission of carbon dioxide, they also increase the complexity of the system.

The complexity of an electrical system is also due to its development through the integration of distributed generation. In the past, distribution was radial, there was only one point that supplied the entire network. However, currently, an increase in the integration of generation distributed through renewable energy (solar and wind) and microgrids have transformed electrical systems into a decentralized and intelligent system consisting of a variety of technologies and decentralized operations [77]. Therefore, smart grids require a set of applications to deal with the complexity and requirements of efficiency, economy, and reliability.

Different applications can be carried out by the smart grid scenario, including smart metering, load management, power distribution automation, pricing, power line interruption management, and line restoration. The communication technologies that can be applied to this network vary according to the application since some applications require a higher data rate than others. Besides data rates, different applications also require specific latency from the network. These requirements will be described following [78].

A. METER READING

Meter reading applications allow power distributors to read consumers' energy meters automatically [79]. Different from conventional automatic meter reading, smart meters allow daily data collection, as well as can be utilized for collecting real-time current and voltage measurements [80], [81]. With Advanced Metering Infrastructure (AMI), a real-time (or near-real-time) bidirectional data flow between user and distributor provides greater precision in power readings, reduces operational costs, and maximizes the benefits of the resources provided by the utility operator. This solution also allows the customer to have greater control of their energy expenses [82].

B. DEMAND RESPONSE(DR)

Demand Response (DR) is a program used by energy utilities to encourage consumers to modify their energy consumption, leading to increased confidence and efficiency in the operation of networks, favoring reduction on consumption, balancing supply and demand, avoiding interruption of the energy supply at peak times, managing electricity prices [83], [84]. The DR program can be classified into: a) based on price, whose tariff models can be Time-of-Use (TOU), Real-Time Pricing (RTP) and Critical-Peak Pricing (CPP); b) based on incentive, which is subdivided into Direct Load Control (DLC), Interruptible / Curtailable Service (ICS), Emergency Demand Response Program (EDRP), Capacity Market (CM), Demand Bidding / Buyback (DBB) and Ancillary Services Market (ASM) [85], [86]. The price-based program is reasoned on changes contained in consumers' energy consumption in response to existing variations, throughout the day, in prices of electricity at a time of purchase. In this sense, the price-based program leads consumers to modify their electricity usage patterns according to variations in electricity prices, instead of directly controlling the use of their electrical equipment [87], [88]. The incentive-based program offers stimuli for uses, such as credits, discount rates on energy bills, or cash to consumers to reduce energy usage during peak system times. However, it is noteworthy that the registration and responses of consumers to this program are voluntary. Some of the existing programs penalize participants for their failures in contractual responses, according to established events [89], [90].

C. SUBSTATION AUTOMATION (SA)

Substation automation is based on the integration of conventional real-time power grid functions to increase system operating efficiency and simplify operations within substations. The main functions supported in this application are those related to critical protection and control scenarios, network fault monitoring, substation, and field equipment diagnostics, as well as providing power network optimization [91].

D. DISTRIBUTION AUTOMATION (DA)

Distribution automation applications provide network structure information, automation control, data communication, and information management for monitoring and controlling of the distribution network. Distribution Automation (DA) helps in maximizing the efficiency of the distribution network by controlling devices, such as bank of capacitors controllers, reclosers, switches, fault detectors, and voltage regulators. This system is usually implemented through open protocol standards, communication over Internet Protocol (IP) networks, and Supervisory Control And Data Acquisition (SCADA) interfaces.

E. POWER QUALITY MONITORING

One of the main objectives of a Distribution System is to supply electricity to consumers reliably and uninterruptedly. Although concessionaires plan their operations with this objective in mind, distribution systems are subject to unforeseen events that directly impact on the quality of the electricity supplied, called electrical disturbances [92], [93]. The integration of distributed generation, among them renewable, can promote a reduction of environmental impact by reducing the emission of carbon dioxide and also a more efficient and safer operation of energy systems [94], [95]. However, this integration is one of the biggest sources of electric power quality disturbances and can cause, for example, overvoltage and undervoltage, increased faults, elevation, sinking, interruption, etc. Therefore, constant monitoring of electricity quality is essential to identify existing disturbances and correct possible flaws in monitoring plans for these events [96]. One way to carry out this monitoring is by installing equipment capable of monitoring energy quality in distribution systems [97]. An essential step to analyze electric power quality is to detect and classify disturbances quickly and accurately, since once a disturbance has been detected and subsequently classified, it becomes possible to determine its causes and adopt control and mitigation measures [98]. Consequently, applications that include detection and classification methods are indispensable so that preventive actions by concessionaires and consumers can be taken regarding load requirements and changes in the system's operation [99].

F. DISTRIBUTED ENERGY RESOURCES (DER)

This application allows renewable sources to provide energy to the distribution network, complementing the mass generation carried out by the generating plants. Energy storage is also taken into account, which means that the excess energy generation is not wasted. This storage will provide power at a later time to the distribution system, as well as complement the fluctuation of energy generation that occurs in renewable energy. Additionally, distributed energy resources enable consumers to sell excess energy generation back to the main grid to minimize their energy billing [100].

G. ELECTRIC VEHICLE (EV)

Electric vehicle applications involve operations performed among electric vehicles or hybrid plug-ins and power grids. This application can operate in two situations. In the first one, called Grid to Vehicle (G2V), electricity flows from the electric network to the Electric Vehicle (EV), recharging its batteries. In the second one, called Vehicle to Grid (V2G), the energy flow from the EV to the energy networks, which means that the EV is acting as a power generator, providing electricity to the grid. In both cases, messages can be exchanged between the grid and the EV. This is an important feature since information about the battery status (temperature, charge level, capacity, etc.) can be adopted by the grid to coordinate the charging flow. Also, these messages can be used to configure the network in case a large number of EV are connected to the grid to charge their batteries (G2V mode).

V. RESILIENCE IN POWER GRIDS

In this section, it will be discussed the state-of-the-art of resilience support in power grids. Three important techniques in this context are: (i) teleprotection of the power grid; (ii) power grid self-healing; and (iii) communication with control centers and reclosers.

A. TELEPROTECTION

Teleprotection is the technique employed in telecommunications-based protection systems to interconnect protective equipment physically distant, enabling quick action in the event of a failure. It aims to act with high speed in case of failure, and it uses the transmission line itself for information exchanging through PLC, pilot wire, microwave, or optical fiber.

The teleprotection system is generally installed in high voltage transmission networks, aiming to prevent instability in the high voltage lines, to avoid damage to equipment present in power substations. Its main function is to monitor the transmission lines, coordinating quick messages between the protection relays (of the network terminals) to fastly isolate potential faults in the network.

Since most power transmission systems are loop-connected, shutdown at both terminals is required to isolate a line fault. To solve this problem, the teleprotection system is comprised of protective relays and teleprotection equipment, both inserted into substations. Then, when there is a fault in the transmission line, the nearest substation protection relay will detect the occurrence of the problem, switching on one side of the terminal; data will be collected by the teleprotection equipment, which will send the information to the other equipment available on the remote terminal for the relay, consequently acting on its respective substation and finally isolating the fault line [101].

For the better performing of the protection system, certain requirements, such as selectivity, speed, sensitivity, safety, reliability, and economy, must be evaluated [102]. In this context, sensitivity is the ability of the system to identify and isolate the faulty circuit with the least possible impact on the network. In other words, it ensures that the smallest part of the entire network is inoperative at any given time, ensuring the operability of the rest of the transmission line.

The requirement for speed corresponds to the situation in which the protection system must act quickly and, if possible, ensure reclosing, making it possible that the network can be minimally affected. Teleprotection guarantees a relative gain over shortening fault time by isolating it by 2 to 3 cycles, while this time can reach 28 to 30 cycles in schemes without teleprotection.

Regarding sensitivity in the teleprotection scenario, the system must be sensitive and reliable and it can identify a faulty or normal condition, making the right decision. Along with sensitivity, the safety requirement must ensure that the protection scheme acts only in fault scenarios.

Finally, the economic requirement is directly linked to the cost and technical-economic feasibility of implementing a teleprotection system to a particular transmission line.

For the elaboration of a teleprotection scheme, some logics can be developed, basically divided between Permissive (Permissive Intertrip, Direct Underreaching Transfer Trip (DUTT), Permissive Underreaching Transfer Trip (PUTT) and Permissive Overreaching Transfer Trip (POTT)) and Blocking, as discussed in [103].

In the Permissive Intertrip method, the relay shuts down the local circuit breaker and simultaneously transmits a signal to the remote terminal in order to obtain a quick shutdown at both ends of the faulted transmission line and isolate it. This type of system is capable of allowing instant tripping for about 80% of the total line length.

By using the DUTT technique, a logic is applied when it is desired to turn off the circuit breaker directly by the signal received from the remote terminal, without a protection criterion from the receiving terminal. It is implemented only in cases in which an incorrect signal received from the other terminal causes the immediate breaker to shut down immediately.

In contrast, in the PUTT logic, the received signal will actuate the circuit breaker only when the distance protection relays have operated, indicating a line fault.

The POTT system trips the circuit breakers instantly when relays on both terminals detect faults in overreaching zones. This method is mainly used on short lines where it is very difficult to perform a sub-range adjustment that works correctly for the network. POTT is typically used for transmission lines smaller than 20km.

Finally, in the blocking logic, the transmitted signal is used to block the protection operation given an external fault. In this case, the most used technique is Directional Comparison Blocking (DCB). Two distance zones are calculated: a fast zone capable of sending a lockout signal to the remote terminal if the fault occurs outside the protected zone in reverse; and a directional overcurrent directional unit capable of inhibiting the blocking signal if the fault occurs in this direction, causing the circuit breaker to shut down if the signal is not present at the remote terminal.

Since uptime, safety and reliability are some of the most important requirements in a teleprotection system for fast and accurate fault detection and isolation, and the methods presented have certain acceptable requirements for good network performance and assurance of quality operability.

Applications in Direct Transfer Trip (DTT) type systems require channel operating times close to 12ms. Operating time is not as critical compared to Permissive and Blocking systems as they have backup functions. The DTT system requires high security to prevent false channel tripping and high reliability whether this application operates as a breaker failure backup [104].

Applications in Permissive Transfer Trip (PTT) type systems require operating times between 12 and 15 ms to allow the remote terminal to operate quickly for all occurrences of internal line faults. This technique requires a security index to prevent the channel from enabling an erroneous protection message, since common network problems occur when there is reverse current in parallel lines. This system also requires reliability to enable high communication speeds at both transmission line terminals [104].

Blocking operations have more critical operating times, around 3 to 5 ms. This time is necessary to prevent the remote terminal from sending excessive protection messages in case of external faults. About security, blocking systems require the minimum, and this is due to the impossibility of false trips by the communication channels used in this approach. Besides, the technique requires high reliability as the transmission system will operate without the teleprotection channel [104].

In [105], Rahman *et al.* reported test results obtained in preparing for migration of San Diego Gas & Electric (SDG & E) substation protection relays from SONET to MPLS. The tests presented in the article have been performed both in the laboratory and in a simulation model using Real-Time Digital Simulator (RTDS). The article outlines the requirements for teleprotection and highlights how MPLS provides techniques to ensure minimal asymmetry by routing and transmitting teleprotection paths over the same nodes of the data network. A methodology on how to apply MPLS in teleprotection was provided. The authors concluded that MPLS networks are a viable communication medium for protective relay telecommunications traffic, if properly designed, considering latency, asymmetry, failover, and availability.

A performance comparison between two teleprotection interfaces can be seen in [106]. The first one is based on a conventional teleprotection framework, supported by IEC 60834-1 standard, while the second one is implemented using a structure similar to the gateway communication system presented in IEC 61850 part 90-1. A performance analysis test has been performed using the Real-Time Digital Simulator, showing significant reductions in the signal transfer time and in the operation time of schemes when using the model based on IEC 60834-1 compared to the conventional teleprotection model. Other studies that address the evaluation of teleprotection systems using IEC 61850 standard can be seen in [107], [108].

B. SELF-HEALING

According to [109], self-healing is the ability of an electrical distribution system to automatically restore its full capacity when a permanent failure occurs. Self-healing power grids can isolate permanent failures and restore distribution service to other areas as quickly as possible and with minimal human intervention. The solution should also minimize the number of users affected by the permanent failure and ensure that the resulting network topology maintains the distribution system quality parameters. Still, according to [109], self-healing capability requires remotely controlled switching devices to be available to isolate fault regions and transfer loads to alternative sources. It also requires direct load control devices to be installed at specific points in the distribution network, allowing less important loads to be de-energized.

The coordination of self-healing mechanisms can be distributed or centralized. In the distributed case, self-healing ability emerges as a result of coordination, communication, and switching through distributed control actions. This approach must be very well coordinated with the dynamics of the electrical loads and the switching capabilities of the protective equipment installed. In the centralized approach, a Supervisory Control and Data Acquisition (SCADA) system receives information collected from smart electronic devices installed on the smart grid and performs self-healing actions at the control center. Therefore, it is the control center that performs the self-healing actions.

A real case with 794 nodes has been performed by Cavalcante *et al.* to evaluate a centralized self-healing mechanism [109]. However, nothing has been commented in the article about the communication technology employed to implement the measures that feed the employed optimization algorithm. Furthermore, no comments have been provided about how control commands were delivered to controlled devices. Centralized solutions are known to have a single point of failure, strict communication requirements to the command center, and limited flexibility.

In [110], Song *et al.* pointed to the need for real-time measurement of distribution network parameters to achieve the so-called environmental awareness property. According to the authors, it is only possible to extend the flexibility and control of the distribution network if the current state of the network is known in advance at the control center.

For a deeper approach to the self-healing concept, the power system can be divided into three broad groups, named as transmission grids, distribution grids, and microgrids.

C. TRANSMISSION NETWORKS

To supervise the power transmission lines, circuit breakers and transformers, advanced sensors; signal processors, and communication networks are implemented throughout the power operator to continuously monitor the line parameters and verify its state of operation. The sensors will provide critical data for network operation, such as conductor temperature, conductor conductivity, and line fault location. By computing the information provided by the sensors, the smart substation in the transmission domain must be able to recover itself after network device failures, natural disasters, and power outages.

In [111], Jiao *et al.* proposed a Wide Area Measurements (WAM) and Wide Area Information (WAI) based control solution to quickly react to overloads and restore the power grid (self-healing). To achieve this goal, it has been proposed to redistribute the energy flow from one transmission line to other lines through a Unified Power Flow Controller (UPFC). Then, nodal analysis is performed through WAM and WAI to jointly relieve overloads and perform precise control. After evaluating the proposed system, the authors concluded that the applied strategy was able to relieve overloads by tens of milliseconds.

In [112], Kezunovic *et al.* proposed to increase the accuracy of fault location in power grids through data obtained by smart electronic devices. Following the premise, it was suggested the installation of phase measurement units next to a GPS, aiming to accurately determine the location of the faults in the network.

In [113], Shim *et al.* employed a Smart Superconducting Fault Current Controller (Smart FCC) to protect the power grid. The protection system was based on the control of the leakage current level using the Smart FCC, which employs a full-bridge thyristor rectifier to control the firing angle of the thyristors and achieves the desired leakage current level.

An approach to control the magnitude of voltage in electric power transmission systems is proposed in the study [114]. This approach determines a sequence of adjustments in synchronous generators, to inject reactive power into transmission systems while reaching an operating point without violations in magnitudes of tension in load bars. All adjustment procedures are supported by a communication infrastructure, which transmits the information used to determine the state of systems and passes commands to be carried out to control devices. In communication infrastructure, all data traffic is provided by WiMAX wireless technology (Worldwide Interoperability for Microwave Access), considering that this technology defines specifications of the MAC and physical layers for wireless broadband access [115].

D. DISTRIBUTION NETWORKS

The current power grid has protection provided by overcurrent relays that perform local measurements of the current value against a time curve. When the current value exceeds a certain threshold at a specified time, the overcurrent relay sends a signal for the local circuit breaker to open it. This action stops the failure, but it interrupts the power supply for users who depend on that line. The threshold values for circuit breakers are assigned from a coordination and protection study for all relays presented in the distribution networks. When major changes are made to the network, these threshold values need to be updated for the new system [116].

Smart power grids will include a large number of smart switches, strategically located in the power grid. These switches will be able to support self-healing requirements and the need for network reconfiguration, ensuring that the load balancing occurs between feeders, obtaining a better balance feeder load and distributed generation capabilities [117].

In [118], Abdelaziz *et al.* proposed an adaptive protection system based on the optimal coordination of overcurrent relays installed in the power grid. The system adapted to network changes, such as load, generation level, or topology changes. Based on these changes, the system updated relay settings to adapt to network changes. To validate the proposed scenario, the authors employed the IEEE 30-bus test platform. After testing, it was confirmed the importance of maintaining optimal relay performance under different conditions.

In [119], Zidan *et al.* proposed a system capable of locating and isolating network failures. It has been able to decide and implement network switching operations to restore out-of-service loads. The system consisted of two layers, in which the first one had the function of monitoring, performing simple calculations, and implementing control actions. Moreover, the agents in the second layer had the function of negotiation. Constraints include voltage and line current limits. The authors took into consideration the load variation to avoid the need for new reconfigurations during the restoration period. The results of the simulation performed using the new structure demonstrated the effectiveness of the proposed control structure.

E. MICROGRIDS

A microgrid is a power distribution system that integrates distributed generators, energy storage systems, and controllable loads [120]. A microgrid can be structured in two ways: networked or islanded. An intelligent microgrid differs from traditional distribution systems in terms of reliability, self-sufficiency, self-healing, and interactive characteristics. According to the IEEE 1547.4 Standard, the operation and reliability of a distribution system can be improved by dividing it into multiple microgrids [121]. For this reason, new models and technologies need to be evaluated to integrate control networks into distributed generation and distribution scenarios [122].

In [120], a communications network allowed information exchange and coordinated control between microgrids. It is an example of a decentralized self-healing solution, and they proposed the concept of networked microgrids, a model that matches what we presented earlier in terms of decentralization and monetization of micro-generation power plants. In [123], Chen *et al.* reconfigured the setup of the power switches using software to provide self-healing and to prevent the spread of attacks.

F. COMMUNICATION WITH CONTROL CENTERS AND FIELD DEVICES

Control centers act on electricity distribution assets, such as relays, field switches, reclosers, capacitor or transformer banks, demand management devices or systems, power storage, and others. They can be connected to network operations centers to enable monitoring of the state of the physical world (a property called situation-awareness). These telemetry devices and data connections can become more widespread as additional intelligence-embedded systems and devices are deployed in distribution networks.

Monitoring, control, and management can be implemented as a combination of software running on general-purpose computing systems, interconnected with data centers and embedded hardware, communications software and systems, technologies embedded in electrical assets deployed at distribution networks or customer facilities. The aim is to provide network load control, critical event monitoring, and device action to contain critical events [124].

The Supervisory Control and Data Acquisition (SCADA) is responsible for the integration of control systems, being able to collect and contextualize data. Therefore, it can be seen as a tool that integrates several applications to optimize, monitor, and control operational data. The SCADA system works at three levels. The first level covers power stations and transmission lines that have equipment for measurement and monitoring. The second level includes the local control center, which encompasses computing servers to process information from equipment at electrical distribution networks and substations. Finally, on the third level, there is the main control, a logically centralized system that concentrates information from local control centers.

These levels result in a large amounts of data which in many cases require real-time support. Therefore, in [125] the authors proposed a way to increase precision and observability using Deep Neural Networks (DNNs); and, in [126], Qian *et al.* contended that when using proper data analytics techniques in SCADA systems, it is possible to identify strange behaviors in the energy grid.

SCADA's potential lies in its integration with other control and management systems, such as the integration with the Energy Management Platform (EMP) and Energy Management System (EMS) to provide quality of service. The integration with databases, which store information from SG, can also be used by energy concessionaires to obtain behavioral patterns of operation, failure prediction, and assessment of the system's state as a whole [127]. The big challenge is sharing this data safely so that it can be used by third parties without privacy issues, as it is difficult for utilities to share their information with possible competitors. Distributed ledger technologies, such as Blockchain (Section V-G) can help on this matter since information can be naturally distributed in a decentralized and private way for authorized parties.

Proper communication among the control system, management, and controlled devices can reduce any complexity or incompatibilities that result from a proliferation of devices or systems of different types, purposes, and suppliers in a distribution network. In other words, it plays a fundamental role in the interoperability of equipment and networks [128], [129].

In SG, confidential and financial information transactions can be exchanged to/from authorized persons, services, and equipment. Dynamic energy markets will demand elastic, trustable, dynamic composable, secure, and trustable services for supporting emerging control and management planes. Through efficient control and management, different bidirectional traffic flows constantly, requiring proper traffic engineering [130]. The joint design of control centers and/or SCADA with traffic engineering and programmable networks, like SDN, maximizes the availability of services, data interoperability, and security [131].

G. BLOCKCHAIN

Satoshi Nakamoto, through the study Bitcoin: A Peer-to-Peer Electronic Cash System, revolutionized the global financial system in 2008 [132]. As one of the pillars of Bitcoin, blockchain technology proved to be innovative and attracted attention from most diverse technological fields, among them, emerging smart grids. Blockchain behaves like a distributed database with nodes connected to one another via a communication network, having as one of its main characteristics the guarantee of accessibility, transparency, immutability, and integrity of the information.

The use of blockchain in smart grid scenarios enables the development of new business models, as well as ways to improve existing models. This technology can be employed in the commercialization of distributed generated energy, access to electric vehicles charging and discharging systems, registration, and traceability of renewable energy generated by third parties, real-time energy markets, providing security tools against cyberattacks on microgrids (Section V-H), among other aspects [133].

In [134], Andoni *et al.* presented a comprehensive review of the use of blockchain technology in energy scenarios. The authors evaluated 140 research projects and startups using blockchain technology, classifying them according to their main characteristics, drawing a profile of relevance for applications demanded in the energy scenario. The study also provided a critical view of the challenges that this technology needs to overcome to become viable in field applications.

In [135], Liu *et al.* proposed an adaptable blockchain with the Iceberg Orders algorithm for planning charges and discharges carried out by electric vehicles in the electricity grid. The main objective of this study has been to develop a solution that helps to reduce costs for final users and to minimize impacts on the voltage fluctuation imposed by electric vehicles on power networks. Simulations have been used to evaluate this proposal, showing that results obtained are promising, presenting a superior performance to a scheme that employed only genetic algorithms, both in voltage fluctuation and in costs imposed on users.

In [136], Wu *et al.* evaluated the use of blockchain technology in demand-side management applications. The authors proposed the use of blockchain to record data from energy calculation flow and the price variations accordingly to demand. Smart contracts (programs that run directly from Blockchain) are used to store data from transactions and carry out asset transfers automatically. A proof of concept implemented results proves the efficiency of the proposed method.

H. CYBERSECURITY

Cybersecurity of smart grid and energy control networks is a multifaceted and complex problem. It includes the security of hundreds of communication protocols, operating systems, distributed systems, equipment, and people. Limitations are related not only to the original design of communication protocols, but also to equipment implementations by suppliers. Moreover, distributed software security is quite dependent on its design quality and implementation. A review of the advances in smart grid cybersecurity data life-cycling is provided by [137]. The work explored the data security challenges from energy generation up to final delivery. It also cited other surveys on attacks and countermeasures in this area.

In [138], Rong Jiang explored the root causes of attackers on energy systems. The paper provides a general description of all security points in a chosen system, establishing an attack tree. The possible objectives of the attackers are recursively divided into sub-objectives, making it possible to find a pattern for possible threads. Three types of energy theft were raised, namely: measurement interruptions, violation of authorized demand, and network changing. They make it easier to tamper with smart meters, creating multilateral fraud, stealing personal data, and countless other crimes.

Maamar and Benahmed [139] explored energy theft detection in AMI using machine learning techniques, performing a general comparison of machine learning models for detecting energy theft based on the extracted information, such as environment types, metrics, and data sets. The most used methods found in this study were, neural networks and support vector machines. The study confirmed that data can be tampered with in an AMI, both locally and remotely. Therefore, applying machine learning to an appropriate selection of data subsets, with the appropriate metrics, would facilitate the detection of suspicious or unexpected behaviors.

Despite the IEC61850 standard and its extension for security (IEC62351), there are still flawed points that need attention. As mentioned in [140], assuming the attacker already has access to the network, the goal will be to repeat control messages to restart the system or messages from changing states, causing major damage. As a countermeasure, key management and signing times in GOOSE could be optimized.

Ustun *et al.* [141], addressed flaws in energy systems cybersecurity, including replay and masquerade attacks, which could directly affect operations on power networks with the GOOSE protocol. To solve these problems with GOOSE, the authors of [142] proposed two modified algorithms: (i) a modified Rivest-Shamir-Adleman (RSA) with different key sizes; and (ii) an Elliptic Curve Digital Signature Algorithm (ECDSA) using novel curves. Therefore, if there is any change in the cryptographic hash of certain information, the message will not be decrypted by the public key. The authors contend that the biggest security problems are linked to companies that produce far end solutions, such as smart meters [143].

When treating cybersecurity with Blockchain, in [144] the authors surveyed on the areas in which the technology has been applied: measurement and control, data aggregation, data management, and operations. Independent Blockchains can be created for any desired application. Data generated at smart grids can be securely inserted and become immutable. Blockchain access software is a point of extreme attention, especially digital wallets. Another aspect is the number of nodes that participate in the network, since small networks may not offer the guarantee of information or computation immutability.

Smart contracts can be employed to monetize energy-related transactions, such as the purchase and sale of energy generated at homes and microgrids. Despite being far from maturity, smart contracts have been very promising to create a decentralized energy market [145]. The deterministic and immutable execution of microservices via smart contracts promises a safer energy market. However, smart contracts are written by humans and therefore subject to unintentional and intentional errors, which can expose valuable assets.

In [146], authors focused on smart meters, in terms of processing capacity and memory, since resources are limited for heavy encryption or decryption calculations. They contended that it is interesting to use one Blockchain to perform not only secure data collection, but also exchanging of measured values. At a hierarchical level above, another Blockchain can be employed to record systems history [147]. This is also an approach taken by Dong *et al.* [148]. The authors also argued that viruses or other threads can break through the defenses of a Blockchain, having access to sensitive immutable data stored there [148].

By establishing an information-centric smart grid (iCenS), Wang *et al.* [149] contended that greater efficiency, fault tolerance, and mobility performance can be achieved for smart grid applications. Information-centric networking (ICN) can protect data by employing self-verifiable identifiers (SVIDs). In other words, the measurement data or control commands could be delivered directly by their perennial verifiable names. Typically, cryptographic hash functions could be employed to generate SVIDs from the binary pattern of information objects. Guo *et al.* [150] is another ICN-based work for energy control networks.

Future Internet architectures (Subsection VI-J) (including ICN) have intrinsic security as one of their main design principles; that is, security, privacy, and trust are inserted since the first day of design. Promising approaches for distributed denial of service (DDoS), spoofing, and many other vulnerabilities are proposed. Novel design ingredients, such as self-verifiable naming, secure name resolution, unique SVIDs, trust network formation, contract-based operation, autonomic self-protecting, self-healing, publish/subscribe communication, data provenance, and integrity are important additions to current security techniques.

VI. COMMUNICATION TECHNOLOGIES FOR CONTROL NETWORKS

Responsible for bidirectional data communication among the present elements in the power grids, communication technologies play a fundamental role in smart grids, as well as mission-critical services. That section details the main statistical and deterministic technologies used in current smart grid scenarios.

A. ETHERNET

Ethernet is a non-connection-oriented packet switching technology defined by a set of the physical layer, data link specifications, functions, and protocols originally developed for computer networks [151]. Since 1985, Institute of Electrical and Electronic Engineers (IEEE) has been working on a set of standards (IEEE 802.3 family) to deliver Ethernet networks on new transmission media, data rates, and with new features. Some standards available for the technology are 10Base-T Ethernet, Fast Ethernet, Gigabit Ethernet, and 10 Gigabit Ethernet. These standards have data rates of 10 Mbps, 100 Mbps, 1 Gbps, and 10 Gbps, respectively [151]. Ethernet's scalability, simplicity, and cost-effectiveness, coupled with its high rates and optical network support, have led many service providers to consider Ethernet in Metropolitan Area Networks (MANs) and WANs, in which it is called Metro Ethernet. In 2001, Metro Ethernet Forum (MEF) was founded to promote worldwide adoption, interoperability, and deployment of Ethernet networks and services that meet telecommunications demands. These efforts led to a new class of Ethernet called Carrier Ethernet.

The International Electrotechnical Commission (IEC) 61850 [152], which consists on the Generic Object-Oriented Substation Event (GOOSE) protocol, is transported directly over Ethernet Virtual Local Area Networkss (VLANs), dispensing Transmission Control Protocol (TCP) over IP and other networking technologies. GOOSE is used for rich semantic communication in protection and control applications to replace cables connecting relays. The IEC 61850 standard adopts modern technologies developed by the computer science and telecommunications industry, such as Object Oriented Design (OOD), Unified Modeling Language (UML), Publish/Subscribe Communication Model, and Extensible Markup Language (XML), for long-term stability, interoperability from different vendors, and reduced teleprotection system engineering time. While GOOSE protocol is seen as a device control protocol (actuators in the utility), other protocols are designed for sensing electrical quantities of interest in smart grids. For example, the IEEE C37.218 protocol [153] is used for synchronized phasor measurement between Phasor Measurement Units (PMUs) and Phasor Data Concentrators (PDC) defining data types, messages, and their formats.

In [154], an Ethernet VLAN is used to carry the GOOSE protocol directly over Ethernet, connecting objects representing power grid devices. In [155], a performance evaluation (fault debug time and recovery time) and a parameter estimation (fault current and trip delay) is performed through a centralized scheme with detailed modeling and co-simulation of all aspects of IEC 61850 network and the power grid. In [156], an experimental validation and performance evaluation of an accelerated protection scheme based on the IEC 61850 is performed. GOOSE protocol messages are evaluated under different Ethernet WAN scenarios. For the worst-case scenario, it was found that there is a significant saving of operating time in the proposed scheme.

In [110], Song *et al.* described the technology landscape used in Korean Smart Distribution Management System (KSDMS) project. IEC 61850 and Distributed Network Protocol (DNP) standards messages have been carried directly over Ethernet [152]. The real-time nature of the power distribution network control problem often has a solution that is independent of TCP/IP technologies. DNP 3 is a protocol employed for communication among components in mission-critical operators and can be used between PMUs and PDCs.

In [157], Fukushima *et al.* aimed to show that Ethernet packet networks can be used as an alternative to Plesiochronous Digital Hierarchy (PDH) and Synchronous Digital Hierarchy (SDH) in transmission line differential protection relays. According to the authors, the sampling synchronization performance of an Ethernet protection relay is compatible with the expected performance of a legacy line differential relay. In the mentioned paper, a dedicated Ethernet protection relay communication network, with a 1 Gbps data rate using a duplicated transmission path and current differential elements, were used.

In [158], Hoga and Wong presented the benefits of using the IEC 61850 protocol compared to traditional communication models used in power substations. In [153], Song *et al.* presented the 61850-9-2 protocol that specifies two communication modes over Ethernet. The first mode is for direct transmission of sampled values over IEEE 802.3 (Ethernet) and IEEE 802.1q (VLANs). The second mode uses client/server communication according to the Manufacturing Messaging Specification (MMS). Both modes focus on communication between PMUs and PDCs. According to [159], the IEC 61850 protocol have been considered for low latency applications and near real-time information exchange, allowing for information exchange among systems: Distributed Energy Resource Management System (DERMS), Advanced Distribution Management System (ADMS) and Microgrid Energy Management System (MEMS). Also, in [160], a variation of the GOOSE protocol, called Routable GOOSE (R-GOOSE), is employed for coordination between substations. A R-GOOSE over Ethernet laboratory implementation has been developed to evaluate the WAN coordination performance and teleprotection applications.

In [161], Han *et al.* proposed a communication architecture using the IEC 61850 protocol for distribution automation, in which communication among control centers and devices located in the field is carried out. In [162], Qureshi *et al.* developed a study on communication infrastructure for substation automation and evaluated the main problems and requirements necessary for adopting Ethernet technology in this context. In [163], Kumar *et al.* proposed automation, protection, and control architecture for a high voltage substation using Ethernet technology to support GOOSE messages exchange among substation and smart devices.

In [164], Cao *et al.* presented a system for automatic energy measurement. The collection and sending of data from sensor nodes to data collectors are carried out through Zigbee technology, while collectors' information is delivered to the servers via Ethernet. The results obtained through simulations prove that the proposed solution is efficient. In [165], Suljanovic *et al.* presented the requirements for energy distribution application deployment, such as distribution automation, AMI, and WAMS. The authors proposed the use of the IP and Ethernet protocols for a smart control network, carrying out a more detailed study in the traffic prioritization systems in the MAC layer.

B. POWER LINE COMMUNICATIONS (PLC)

Power line communications or power line carries are a very popular technology in the smart grid landscape [166]. This technology employs existing power lines to transmit data, eliminating the need for new infrastructure, making implementation cost less than other possibilities. PLC technology can be divided into four categories being them, Ultra-Narrow Band Power Line Communication (UNB-PLC), Narrowband Power Line Communication (NB-PLC), Quasi Band Power Line Communication (QB-PLC), and Broadband Power-Line Communication (BB-PLC) [167]. The two main PLC technologies applied to the smart grid scenario are NB-PLC and BB-PLC, which will be detailed below.

1) NB-PLC

In NB-PLC technology, data is transmitted in a narrowband operating in the range of 3 kHz to 500 kHz [168]. This technology can be used in a variety of NAN applications, such as distribution automation, online diagnostics and monitoring, and fault detection [167]. The range of frequency bands available for this technology may vary according to the region. In Europe, the 3 kHz to 148.5 kHz band has been defined [169]. In Japan, the defined band range is from 10 kHz to 450 kHz. In the United States, the defined band range is from 10 kHz to 490 kHz, and in China, the defined band range is from 3 kHz to 500 kHz [170]. Several standards have been established for NB-PLC technologies, including PRIME, G3-PLC, IEEE 1901.2, ITU-T G.hnem, IEC 61334, IEC 62056, and IEC 14908-1 [171].

2) BB-PLC

BB-PLC technology was created to provide real-time connectivity to customers through radio frequencies in the power grids. BB-PLC technology works in the operating band ranging from 1.8 MHz to 86 MHz, providing, its customers with rates in the order of hundreds of Mbps [172]. This technology can be applied in various areas of the smart grid, addressing the HAN and NAN domains. Some of these applications are Smart metering, Distributed Energy Resources, electric vehicles, last-mile communications, among others. Several standards have been established over time for BB-PLC technology. These include HomePlug AV, HomePlug Green PHY, HomePlug AV2, ITU G.hn, ITU-T G.9960, ITU-T G.9963, and IEEE 1901-2010 [173].

In [174], Sendin *et al.* presented a communication architecture in a smart grid, using PLC technologies that have already been tested and implemented in the field by the Spanish company Iberdrola. In this architecture, BB-PLC technology has been adopted for telecommunication backbone between secondary substations and NB-PLC (PRIME) for interconnection with smart meters. The network performance appraisal has been performed through actual implementations made by the company, showing that PLC is a suitable and very advantageous solution for smart grid deployments.

In [175], Cortes *et al.* evaluated the performance of NB-PLC technology in current AMI applications, taking into account urban, semi-urban, and rural environments, as well as assessing the influence of the cable type used for low voltage network architecture. The solution has been also evaluated by the authors by placing a data concentrator on the medium voltage side of the network, focusing on environments in which the number of clients connected to the medium and low voltage transformers is low. This solution was evaluated using the CENELEC-A (3 kHz to 95 kHz) and FCC (150 kHz to 500 kHz) bands. Performance estimation has been carried out through systems implemented in the field. After the performance evaluation, it has been concluded that the best result was obtained in semiurban areas. The worst performance considering the type of cable used in low voltage networks has been obtained in conventional suspended cables. Regarding the implementation of the data concentrator on the medium voltage side, it has been found that it is possible to use NB-PLC technology in this type of application.

In [176], Milioudis *et al.* presented a high impedance fault identification and location system in multiconductor power distribution networks using PLCs devices. Architecture has been proposed by the authors. For fault detection, a PLC device has been placed at the beginning of the monitored line, measuring the input impedance differences at some specific frequencies, and a pulse injection system is used to locate them. For the evaluation of the proposed system, simulations have been performed, using as a basis a three phases medium voltage multiconductor system. After the simulations, it has been verified that the fault identification and localization method achieved satisfactory results. Moreover, the installation of the equipment used for fault detection in one phase has been sufficient to provide the detection and localization in all analyzed conductors.

C. DIGITAL SUBSCRIBER LINES (DSL)

DSL technology reuse fixed telephone lines to send data [177]. This technology has as one of its main advantages the possibility of employing an infrastructure that is already available to the utilities, thus avoiding the installation cost. The DSL technologies are Asymmetric Digital Subscriber Line (ADSL) [178], which offers a downstream rate of 1.5 Mbps to 9 Mbps; ADSL 2, with a downstream rate of up to 12Mbps; ADSL2 +, with a downstream rate of up to 24 Mbps; and also the Very high-bit-rate Digital Subscriber Line (VDSL) technologies. This family also includes VDSL2, in which VDSL offers a downstream rate from 13 Mbps to 52 Mbps, and a downstream rate of 100 Mbps. However, these values may vary widely by the implementation, suffering large reductions in transmission rate with increasing distance [179].

In [180], Laverty *et al.* observed the difficulty of designing systems that could not only withstand the demand for rapid growth but also support high data rates and real-time communications for smart grid telecommunications systems. In this context, they proposed to analyze various technologies (DSL, WiMAX, 3G, and GPRS) for last-mile deployment and suggested a telecommunications network model for smart grids. The authors concluded that to connect customers to data concentrators, PLC technology could be used to it prevent the installation of new infrastructure because it uses power lines as a means of communication. However, it could not comply with the backhaul requirements of the data concentrator, opening the possibility for other technologies, such as DSL, WiMAX, or others.

Baba *et al.* evaluated the problem of frequent power outages and blackouts due to peak West Bank surpluses and proposed an intelligent network based on ADSL communication technology, in which an integrated control unit is used to collect consumer data, communication, and load control of users [181]. The validation of the network was performed through simulations, took into account the load data in the last years. Then, it has been concluded from the simulation results that the system could solve peak hour blackout problems through demand management.

D. OPTICAL NETWORKS

Fiber-optic technologies provide high transmission capabilities, low latencies, wide bandwidth, high reliability, electromagnetic interference immunity, and coverage of large geographic areas without loss of quality [182]. On the other hand, its implementation cost may be significant for some technologies, which may make it difficult to choose the technology for smart grids. The main fiber technologies in the scenario are PDH, SDH, OTN, EPON, RoF, and GPON. Following it will be described some fiber optic networking technologies and their applications in the smart grid scenario.

1) PDH

Signal multiplexing systems have emerged with the advent of the need for telephone line expansions. Initially, 32 voice channels with 3.4 kHz were converted from analog to digital using the Pulse Code Modulation (PCM) technique and time-domain multiplexed. This technique was recognized by the acronym PCM/TDM, in which TDM stands for Time Division Multiplexing, which is widely used in the mission-critical scenario up to these days. TDM networks allow the user to transmit 32 channels of voice over a single medium, but at different times. Due to its near-synchronous network nature, it was called Plesiochronous Digital Hierarchy (PDH) multiplexing. Two distinct signals are called plesiochronous when they have the same transmission bit rate at the same time.

The PDH system uses a hierarchy of digital signals. For this technology, there are three different world standards: the European, the American, and the Japanese. According to the European standard, hierarchies (E1 and E2) are standardized by the ITU-R G.703 recommendation, while hierarchies (E3 and E4) are standardized by the ITU-R G.704 recommendation. Their respective PCM encoding, voice, and bitrate definitions are standardized by the ITU-R G.701, ITU-R G.702, ITU-R G.711 Recommendations, respectively.

The alignment of each multiplexing frame at each hierarchical level is defined in Recommendation ITU-R G.706. The specifications of the network interfaces with each hierarchical level and also the interconnection with digital synchronous multiplexing are presented in ITU-R G.708 and ITU-R G.736 recommendations. Interconnections with optical interfaces are presented in ITU-R G.709 Recommendation. ITU-R G.734 Recommendation deals with near-synchronization of PDH multiplexing, while the ITU-R G.735 Recommendation deals with the tolerance interference levels between the multiplexed signals.

Peer-to-peer PDH solutions provide propagation delay and bit error rates lower than the values specified for teleprotection services. However, the number of hops in PDH networks can compromise the protection action time. Moreover, the solutions presented in the switching of protection devices are proprietary. The GARD 8000 model equipment described in [183] has a PDH interface for use in teleprotection services. With a modular structure, it can be configured for teleprotection in the 2 Mbps data beam or individually in the 64 Kbits voice channel [183]. In [184], the IMUX2000 T1/E1 model equipment offers a PDH solution with teleprotection channels for operating data networks. The device also allows simultaneous transport with voice, video, data, and Ethernet signals. The total bit rate of transmission corresponds to the first hierarchy in European (E1) or American (T1) standards. It is a suitable solution for operating in networks with hot-standby, ring, and spur topologies. The equipment meets IEEE/ANSI specifications in C.37.90-1989, C.37.90.1, and C.37.90.2 standards for Surge Withstand Capability (SWC), Fast Transients and Electromagnetic Interference (EMI), and Radiated Electromagnetic Withstand Capability (REWC).

2) SDH

As the demand grew up, it was clear that 2 Mbps (T1) systems would not be sufficient to meet demand on the network trunk. Then, the development began for higher levels that would be used to multiplex multiple T1 signals into a single higher-level signal. Then, it has been developed and standardized by ANSI, the Synchronous Optical Network (SONET) for the USA. At the same time, in Europe, the Synchronous Digital Hierarchy (SDH) circuit switching technology was developed and standardized by ITU-T for international usage.

The SDH network consists of equipment that operates synchronously. Each device has an internal slave clock that must, directly or indirectly, be synchronized with a high stability clock, called the Primary Reference Clock. Since information is carried as bitstreams, equipment synchronization is critical for the various signals to be multiplexed and demultiplexed properly with minimal deviation from the nominal rates of each level. These characteristics are essential for teleprotection systems on the market, so that the information arrives correctly at the ends of the power transmission lines, avoiding erroneous relay tripping.

SDH technology has Automatic Protection Switching (APS) features that allow automated switching of virtual channels through which circuits pass in the event of a failure. However, standby virtual links must be available in a failure event so that protection mechanisms can switch to them. In this context, virtual channels with the same rate as operating channels can be reserved (known as mirroring), lowering network utilization to less than 50%. This is the price that the user pays for protection for each mission-critical channel in the network.

To carry Ethernet traffic over SDH, Ethernet frames must be encapsulated before mapping them to the SDH network [151]. This solution is known as the Next Generation (NG) SDH. This evolution allows the delineation of Ethernet frames inside SDH containers. To delineate means determining the beginning and end of Ethernet frames within the continuous bitstream of circuit switching. Generic Framing Procedure (GFP) technology is used for this purpose. The Ethernet MAC frame octets from the Destination Address field up to the error checking field are encapsulated in the GFP information field.

According to Nokia [185], solutions that combine SDH core network and PDH access are commonly used by power utilities to comply with the communication requirements in high voltage networks, including teleprotection and remote reclosing actions. NG-SDH offers high availability, comprehensive manageability, and many network monitoring features, which is ideal for mission-critical. Also, according to Siemens, Ethernet over SDH (EoS) provides low latencies for operating network control traffic.

In [151], the advantage of NG-SDH in terms of link utilization over a pure SDH solution has been proved. The NG-SDH solution allows you to carry deterministic and statistical traffic on the same equipment, which is an advantage when you want to serve both worlds (packets and circuits), simultaneously. However, NG-SDH and PDH networks have high Operational Expenditure (OPEX). Also, the demand for packet technologies is increasing significantly, according to the same reference, such as devices based on IEC 60870 and IEC 61850 remote control (data acquisition and supervision control) standards [152], [186], [187].

In [188], Enose proposed a management system for an intelligent network, composed by typical energy concessionaires and telecommunications networks. In this study, PDH, SDH, SONET, and WDM networks are presented as possible candidates to provide communication among control centers and substations. In [189], Celebic *et al.* evaluated the problem of telecommunication channels redundancy in teleprotection systems and concluded that in most cases the use of Ethernet over SDH presented good results. Several tests performed to assess whether the proposed system meets teleprotection requirements, obtaining satisfactory results, and complying with requirements of the IEC-60834 standard.

3) EPON ETHERNET OVER PASSIVE OPTICAL NETWORK

EPON technology was based on the need to transmit the Ethernet frames on a single optical fiber for two-way data transmission, as defined by the Ethernet standard, or both signals from network terminal to hub direction; or in the opposite path. This is the main feature that sets EPON apart from Gigabit Ethernet over Passive Optical Network (GEPON) technology.

By using a single fiber for transmission and reception of data, EPON needs to separate data from each direction of transmission and allocate it at different wavelengths. Then, EPON needs to share the same wavelength with different network terminals (up to 64 terminals per PON port). For this, in EPON technology it is necessary to allocate transmission resources for each sense of communication, and in this case, there are no bandwidth control or traffic control systems. Therefore, system performance always points to underutilization of physical resources [190], [191].

In [192], Takagiwa *et al.* proposed a service-oriented network architecture for applications in the electrical system. EPON technology has been used as an access network, transferring information from the customer's domain to the energy company's data server. In [193], Inga-Ortega *et al.* presented a solution for AMI application, in which data is collected from smart meters and sent to data aggregation points through a wireless mesh network, connecting HANs and NANs. Data is sent to central offices using an EPON network optimized by WDM technology. In [194], Yong *et al.* evaluated the use of EPON technology as a connectivity infrastructure in smart substations, considering the requirements and characteristics of the energy grid. Results obtained by the authors show that technology meets requirements for bandwidth, reliability, and real-time operation. In [195], Ahmed and Kim proposed a solution for DER application. In this scenario, EPON technology has been used to provide communication among wind turbines and the control center.

Sitian *et al.* proposed a method for automation of power distribution using EPON technology and the Identity-Based Cryptography (IBC) method to favor a secure power distribution system [196]. Based on the proposal, the authors concluded that although several communication technologies can be used in the context of energy distribution automation, EPON technology can be implemented, ensuring satisfactory results. In [197], Zhongwei proposed the creation and implementation of a communication system for FAN networks, based on EPON technology and applications made in the power distribution domain, not only for field applications but also for client domain applications. Through this study it has been concluded that the system is robust, meeting the expectations of the authors.

In [198], Jie *et al.* evaluated the possibility of using EPON communication technology for distribution automation, taking into account requirements of reliability, scalability, CAPEX, OPEX, bandwidth, and security. An access network solution automating energy distribution has been presented by authors. In [199], Sun *et al.* proposed a three-layer communication architecture for control of energy grids. The architecture is based on a centralized controller that employs EPON technology as networking technology among central node, substations, and smart devices located in the field.

4) PoF POWER OVER FIBER

The Power Over Fiber (PoF) technology enables to provide electrical power through fiber-optic links up to a remote photo-voltaic receiver. In C-RAN architectures, PoF might be used for simplifying the overall power supplying of remote units, since their number will increase, as well as management and operational expenditure costs [200]. In this context, PoF comes out as a potential solution for simultaneously providing optical data and power using a single optical fiber. Employing optical fiber to transport power brings some benefits to the systems, including electromagnetic immunity, lighter weight in comparison to the conventional power lines, and easy implementation. On the other hand, PoF has the drawback of having lower power transmission efficiency than the conventional power lines [201].

Indeed, a special optical fiber can be used for simultaneously transmitting data and power in PoF links. In [202], Carmen Vázques *et al.* proposed the integration of PoF to a fronthaul from a 5th Generation of Mobile Networks (5G) radio access network, by using multicore fiber and aiming to deliver power and data signals at Remote Antenna Units (RAUs). Another PoF technique using a double-clad fiber is demonstrated in [203]. The aforementioned technique has been employed in Radio Over Fiber (RoF) systems, to feed a large number of RAUs and provide data transmission. In Internet of Things (IoT) and power grid frameworks, PoF technology provides an economic and social value solution, which enables remotely feeding sensors and control electronics in a high electromagnetic interference environment. Furthermore, smart intermediate nodes can centralize the power source for distributing energy on demand, resulting in a system energy efficiency optimization [204]. Finally, PoF might be efficiently used for fulfilling the requirements of electrical power supply in smart grids, aiding the integration of energy and information industries in a single system [205].

In [206], Rosolem conducted a study on PoF technology, evaluating its main components, limitations, and applications in scenarios like access networks and smart networks. In [207], Cheng *et al.* evaluated PoF technology as an alternative to solar panels and voltage dividers (employed to power sensors and smart devices in high voltage lines). In this scenario, it has been proposed an adaptation of the PoF receiver to restrict the effects produced by the environment on the power supply. Moreover, it has been proposed a multicore fiber to reduce the cost and difficulty to deploy optical communications when compared to several single-core fibers. In [208], Rosolem *et al.* proposed a sensor for monitoring partial discharges in high voltage transformers bushings. In this context, PoF technology has been responsible for feeding the sensor, while another fiber has been subject to sending the collected data to a control center.

5) GPON GIGABIT-ETHERNET PASSIVE OPTICAL NETWORK

In the same context of EPON technology, GPON technology has its particularities, especially in terms of security and band allocation control for its network units. Working in a centralized star topology, it has enough features to meet traffic demands of up to 2.5 Gbps from the hub to the network units served and up to 1.25 Gbps in the opposite direction. GPON technology also supports other predefined rate standards.

In this protocol, safety aspects were designed to include native encryption and the option to encode data. Since GPON employs optical transmission and guarantees its bandwidth control characteristics, it works with a maximum distance of up to 60 km between the concentrator and one of its serviced units. While an EPON concentrator supports serving up to 64 endpoints, GPON supports up to 128 serviced terminals per PON port [209].

GPON brings to the smart grid broadband connections and very low packet transfer delays since its transport structure works with frames of 125 μs. That's why the latency is so small and the jitter is very low. These features can ensure that applications, such as telemetry, telemetering, remote control, among others can be used very easily. GPON broadband is also suited to the characteristics of monitoring services using video and/or audio media [210].

6) OTN OPTICAL TRANSPORT NETWORKING

OTN technology has been idealized to allow the optimization of customer signals transport through an optical network, allowing better utilization of available bandwidth [211]. Its standardization is performed according to the ITU-T G.872 standard. In this technology, the data referring to each of the clients is transported in a transparent container. Therefore, the client's native communication structure is maintained, as well as information regarding time and data management.

As one of its key advantages, OTN technology provides the possibility of transporting different types of traffic (SDH, PDH, Ethernet, IP/MPLS, etc.) over a single Optical Transport Unit (OTU) frame [212], [213]. As the technology provides the possibility of coupling different types of protocols in a single structure, there will be the possibility of different sizes for these structures, and then the OTU frames will be composed of several Optic Data Unit (ODU) containing the customer data [214].

Equipment manufacturer Ciena advocates the application of these networks to teleprotection, especially where performance, reliability, security, and low latency of deterministic networks are essential [215]. ABB also supplies OTN equipment for teleprotection, such as the FOX660 model, which is aimed at the power utility core network [216].

In [217], Wu *et al.* evaluated the efficiency of applying OTN technology in smart grids using a Levenberg Marquardt based Backpropagation (LM-BP) algorithm. The MATLAB simulation tool has been adopted to feed data from a company that adopted OTN technology in smart grids, using the LM-BP algorithm. Results obtained showed that the proposed model, compared to a traditional BP, has been able to reduce time spent in iterations and provided optimized algorithm results.

7) WDM (WAVE DIVISION MULTIPLEXING), DWDM (DENSE WDM) AND UDWDM (ULTRA DENSE WDM)

WDM technology aims to expand optical network capacity through multiplexing signals at various wavelengths on a fiber, meeting the need for resource allocation and communication control between network elements. To this end, WDM technology splits the fiber optic capacity spectrum into channels with certain bandwidth and guard bandwidth between channels. Each of these channels is then treated as a data channel dedicated to exchanging data between two specific points.

With these features, WDM technology is only a ‘‘mean of transport’’ for other technologies such as Ethernet, SONET, TDM, PDH, SDH, among others. For example, WDM optical network elements (WDM add/drop multiplexers or optical interconnections) can interconnect IP routers, enabling the establishment of a transparent light path (optical channel) between two IP routers or equipment of some other technologies. Routers essentially become neighbors over a transparent optical network. This kind of flexibility implies that the topology assumed by IP routing protocols, such as the Open Shortest Path First (OSPF) protocol, may change as traffic conditions vary [218].

The DWDM and UDWDM variants deal with the transport channel density of each of these technologies. The evolution from WDM to UDWDM has been made possible by improved quality of lasers, optical generators, and light receivers, as well as optical amplifiers. The greater the number of channels within the same fiber spectrum, the greater the capacity of that transmission medium. These optics-dense technologies can offer rates above 1.6 Tbps [219].

As such, OTN and WDM are complementary technologies that are widely used as high capacity data transport network technologies, usually, as IP transport backbone for providers, telecom operators, and high capacity transport demand [220].

Power utilities themselves also use these technologies to transport data from one unit (substations, etc.) to another via Optical Ground Wire (OPGW) cables [28].

In [221], Xiaorong *et al.* evaluated a Wide-Area Measurement System (WAMS) integration current Internet protocols with WDM. Authors concluded that WDM can carry IP traffic, reducing the amount of equipment needed, the complexity of network configurations, with acceptable cost, while increasing efficiency in information transmission.

In [222]–[224], WDM and DWDM technologies have been encompassed to provide improvements to applications based on PON / GPON / EPON technologies. With this, the authors contended it is possible to achieve greater bandwidth, security, and protocol transparency.

E. FIBER-WIRELESS NETWORKS

Modern communication systems exploit a set of technologies for transporting and transmitting Radiofrequency (RF) signals between the final users and the core network. Fiber-Wireless Systems (FiWi) enables us to take advantage of both optical and wireless emerging technologies in a unique technological solution. Such systems have become mature with the evolution of microwave photonics techniques, coherent light sources, reduced attenuation from optical fibers in conjunction with high capacities wireless communications techniques [225], [226]. FiWi systems based on RoF technology have been recognized as an important player for the future mobile communications networks implementation, including 5G and 6th Generation of mobile Networks (6G), to favor the simultaneous transmission of multiple RF signals between Base Station Transceiver (BTS) and RAUs [13]–[15]. Therefore, it becomes possible to exploit the existing optical infrastructure, as well as its capillarity for creating a broadband radiofrequency distribution network.

RoF solutions might be applied to FiWi systems for transporting analogue (A-RoF) or digital (D-RoF) signals over C-RAN architectures [227]. In summary, the RoF technique performs electrical-to-optical conversion and optical-to-electrical conversion, addressing communication links transport and distribution. Currently, D-RoF is widely employed in C-RAN architectures for transporting digital samples of RF signals from CO and RAUs. D-RoF can employ Common Public Radio Interface (CPRI), Evolved CPRI (eCPRI) and Open Base Station Architecture Initiative (OBSAI) protocols in fronthaul implementations [228], [229].

In [230] Xu *et al.* proposed a method for load balancing and dynamic allocation of resources in Fi-Wi access networks, so that it was possible to achieve the QoS requirements necessary for the smart grid applications and to optimize networking resources allocation. Simulations were used to evaluate the proposed solution. Results confirmed the proposed method functionality, presenting better use of resources, and making the network more balanced and economically attractive. In [231], Sevilla *et al.* presented a Fi-Wi architecture that includes telephony services and AMI applications as primary and secondary services, respectively. The architecture has been planned to take into account scalability requirements in situations of uncertainty during an increase in consumer demand. The results obtained show that it is possible to implement large-scale Fi-Wi networks, taking as a reference an adequate growth in consumer demand over time.

Liu *et al.* [182] evaluated the problem of power grid recovery in cases of failure and proposed a smart grid architecture. The approach is reasoned in Fi-Wi technology, which provides resilience and adequate latency values when sending information in failure situations. The authors suggested the use of a heuristic clustering algorithm so that sensors are not affected by the failure, being able to find the best routes for information exchange. Results obtained proved the proposed solution's effectiveness. In [232] Guo *et al.* also evaluated the acquisition of data in a smart Fi-Wi communication network after failures occurrence. The authors assessed the performance of three algorithms to optimize paths after failure scenarios, which are optimal enumeration routing algorithm (OERA), greedy approximation routing (GARA), and heuristic greedy routing (HGRA). Results obtained by experiments showed that the GARA and HGRA algorithms achieved path optimization and computational efficiency superior to the OERA algorithm.

A Fi-Wi communication network for AMI applications has been proposed by Inga *et al.* [233]. In this proposal, smart meters are coordinated by a central office. For this solution, a heuristic process has been applied to supply the ideal selection of cell base stations, to form an optimized path for each smart meter. Results obtained in the study show that it is possible to quickly find possible routes to connect smart meters to cell base stations.

F. MULTIPROTOCOL LABEL SWITCHING (MPLS)

MPLS technology intelligently proposes to add the advantages of routing with efficiency and by a reservation of resources in virtual circuit-based packet switching networks. In MPLS, there are two types of routers: the Label Edge Router (LER) and the Label Switch Router (LSR). The first one is located at the edge of the network with the primary function of sorting and choosing the appropriate labels for each packet stream at the gateway entry, removing labels on network output, and converting IP packets to MPLS. The second one consists of high-speed computers located at the core of the network whose primary purpose is to forward packets quickly.

The adoption of IP technologies by the power utilities for mission-critical scenarios is getting closer, once the proposed smart grid's ideals are more widespread on the power industry, tied to the benefits offered by these technologies and the end of the life cycle of TDM technologies. Thus, MPLS technology is a relevant name for the scenario in the coming years [105], especially in developing countries, such as Brazil, India, etc.

In [234], Huawei presented the benefits of migrating the legacy teleprotection system based on TDM technologies to MPLS technology. In [235], IP / MPLS and LTE technology for distribution automation in FANs have been suggested. In [236], Yaghmaee *et al.* proposed a combination of MPLS technology and optical fibers to create a backbone network in energy companies. In [237], PremKumar and Saminadan encompassed MPLS traffic engineering in an IEEE 30 bus network. The authors applied this system in a wide-area monitoring application. The solution has been evaluated using the OPNET simulator, and results showed that the solution can offer a large number of benefits and improvements when comparing to the traditional TDM system.

Jin *et al.* evaluated MPLS_VPN traffic engineering to offer isolation and greater security while exchanging energy distribution control information [238]. Simulations carried out showed that the system can provide isolation and, consequently, improved security in the communication network. In [239], Blair *et al.* proposed the use of MPLS technology to provide secure and real-time communication in differential protection systems. Results obtained in this study show that it is possible to perform real-time encryption of teleprotection system data, without injuring it. In another study [240], Blair and Booth evaluated a real-time teleprotection system using MPLS over xDSL. Moreover, in [241] Nokia presented its teleprotection solution based on IP / MPLS substations automation, covering the communication among substations and the control centers of energy companies.

1) MPLS-TP

MPLS Transport Profile (MPLS-TP) is a set of MPLS protocols that are being defined in the Internet Engineering Task Force (IETF). MPLS-TP is intended to be a simplified version of MPLS, in which some of the technology's original features have been disabled. In this simplified version, it is possible to manually configure the Label-Switched Paths (LSPs), as well as the control plane features presented in the original version. Another feature of the technology is the independence from the IP layer functionality about Operations, Administration, and Maintenance (OAM).

MPLS-TP technology has been quoted as a successor to TDM technologies in power utilities since it is possible to maintain the attributes of legacy technologies. This is accomplished by emulating TDM transport via resource reservation in the packet network and synchronization of the present elements. The efforts to create this technology were mainly driven by the disadvantages presented by IP/MPLS when applied to metropolitan transport networks.

Mission-critical applications demand a high level of precision regarding the synchronization of existing elements in the network. Some of these applications are circuit emulation, Intelligent Electronic Devices (IEDs) control, teleprotection, among others. In the case of IP technologies synchronization is not performed natively, some techniques should be used, and the most common ones are SyncE and IEEE 1588v2 standard [242].

The deterministic performance offered by MPLS-TP (latency, jitter, synchronization), as well as the use of bidirectional LSPs for symmetrical communication, has promoted the interest in using MPLS-TP for mission-critical control networks. In [239], Blair *et al.* demonstrated that real-time encryption of protection traffic on IP/MPLS networks is possible with a negligible impact on differential protection system performance and operation. Two methods to improve the delivery of teleprotection functionality on IP/MPLS networks have been investigated. The first one employed real-time encryption of IP/MPLS teleprotection traffic, in which impacts have been evaluated in the context of the IEEE C37.94 and IEC 61850 protocols (using the Sampled Values (SVes) and GOOSE approaches) for differential current protection. In the second method, asymmetric delay compensation has been evaluated, since delay asymmetries are inevitable in packet networks. The article also showed how the impact of asymmetric delay can be minimized to avoid the potential malfunction of teleprotection relays.

In [105], Rahman *et al.* reported test results obtained in preparing for migration of San Diego Gas & Electric (SDG & E) substation protection relays from SONET to MPLS. The tests presented in the article have been performed both in the laboratory and in a simulation model using a Real-Time Digital Simulator (RTDS). The article outlined the requirements for teleprotection and highlighted how MPLS provided techniques to ensure minimal asymmetry by routing and transmitting teleprotection paths over the same nodes of the data network. A methodology on how to apply MPLS in teleprotection has been provided. The authors concluded that MPLS networks are a viable communication medium for protective relay telecommunications traffic if properly designed, considering latency, asymmetry, failover, and availability.

In [243], Bachli *et al.* introduced how teleprotection applications can be deployed over packet WANs, ensuring the application-specific performance parameters are required. Tests with five 10 Gigabyte Ethernet hybrid circuit/packet multiplexing platforms using MPLS-TP technology have been performed. The system has been synchronized via SyncE and PTP protocols. MPLS-TP provided circuit emulation over bidirectional LSPs for carrying differential protection. A rigorous protection traffic scheduling scheme on network nodes has been adopted. The use of enhanced synchronization features that integrated circuit emulation, MPLS-TP, SyncE, and PTP enabled guaranteed performance for this critical application, even under extreme conditions. According to Bachli *et al.*, reliable differential protection transport over MPLS-TP/Ethernet packet networks can be provided.

In [244], Rafael Moreira presented a discussion about IP application over MPLS-TP and Ethernet for teleprotection. It is a solution from ABB company. According to the author, MPLS-TP offered important OAM capabilities to improve supervision in packet networks, including support for ring topology and redundancies: 1 + 1, 1: N, and 1: 1. The author also commented on the low use of SDH for a large volume of TDM packet transmissions. Despite the NG-SDH improvements, the SDH packet encapsulation process is still an adaptation, with other limitations, such as high cost, complexity, lack of flexibility, etc.

G. CELLULAR NETWORKS

Cellular networks have changed the way society communicates by making personal communication possible. From its first generation to its fourth-generation mobile networks have evolved aiming for providing connectivity for the users, which demanded a voice, Internet browsing, and media sharing services [245]. Upon the 4th Generation, the mobile network has not been designed to address the requirements of other industries and, therefore, its usage in smart grid applications was limited. Workarounds and adaptations have been made to exploit 2G-based networks for IoT applications with limited success and the latest version of 4G networks, knows as LTE Pro, introduces the NB-IoT operation mode, which improves the support provided by mobile networks for IoT applications [235].

LTE has been evaluated by power utilities to assist in smart grid applications, although this standard has not been designed for this purpose. Nevertheless, some requirements for NAN applications has been addressed in this approach, including the characteristics of data being exchanged through the network, differentiated quality of service for real-time broadcasts and non-real-time broadcasting, network access across many devices, congestion control, delayed transmissions, network reliability, flexibility in the frequency spectrum and safety [246]. The LTE standardization process, realized in 2004, defined important requirements, such as 100 peak data rate of 100 Mbps for the downlink and 50 Mbps peak data rate for the uplink, considering 20 MHz bandwidth allocation, and end-to-end latency of less than 100 ms [247]. This technology can be applied in energy distribution automation, AMI, demand response, restoration monitoring, and network fault detection [248].

In [249], respecting the reliability and latency requirements provided by IEC61850, Flammini *et al.* proposed the performance analysis of a public LTE network for smart grid automation. For evaluation of the network performance, the authors built a test platform using two Artic LTE routers, connected using 4G LTE technology to the M2M gateway. The gateway creates an Ethernet bridge across 2 VPNs, ensuring that data is transmitted over the same LAN. The platform captured the Round Trip Time (RTT) of the communications. Based on simulation results, the authors concluded that a public LTE network can be used to provide communication for secondary tasks in smart grids.

In [250], Sanchez *et al.* presented a joint project between the Grenoble Institute of Technology (Grenoble-INP) and Orange Labs to evaluate the performance of LTE technology in power distribution network applications. First, authors searched for applications that required low latencies and then proposed two scenarios for network evaluation. In the first one, the over-current protection system in the network has been evaluated, while in the second one, the selective interlocking logic protection system has been considered. To measure the network performance, an interface has been created between the testing platform in G2ELAB and the 4G LTE network in Orange Labs over a Com4Innov network. After testing, it has been concluded that latencies measured in both scenarios were in accordance with the requirements of the French Distribution System Operator (DSO) and also proved the reliability of LTE for smart grid applications.

Inga *et al.* proposed solutions based on LTE technology for AMI applications in smart grids [251]–[253]. Heuristic models have been proposed for the optimization of communication networks, in which the location of base stations is established taking into account the range and capacity of the LTE network. This enabled to reach a large group of smart meters. Results obtained through experiments showed that network optimization appends in a cost reduction for the final solution. In [254], Yaacoub and Abu-Dayya evaluated the functionality of an automatic meter reading application through spectrum bands that are not being used by LTE networks. The system has been evaluated through simulations and showed that it is possible to allocate a large number of smart meters in a limited coverage area, providing real-time data communication.

LTE-A technology can provide a communication network among users and the utility in AMI applications. A study conducted by Haddad *et al.* has focused on security requirements for communication networks serving this solution [255]. Results pointed out the efficiency of the proposed system, confirming a safe environment with low bandwidth requirements. Still regarding the application of AMI, in [256] Arias *et al.* also proposed an approach based on LTE technology, while in [257] Kavithakumari *et al.* reported a solution grounded on GSM technology.

In [258], Chandra *et al.* proposed a distribution automation system with GSM technology to control and monitor relays remotely. In [259], Elkadeem *et al.* provided an architecture for the automation of an energy distribution system. A GPRS network has been adopted to communicate the devices located in the field with a substation gateway. In [260], Cheng *et al.* performed the evaluation and implementation of an LTE communication network for a Distribution automation application that provides high reliability and low latency. Results found during the study proved that LTE is a strong candidate for DA applications. In [261], Guo *et al.* implemented a distribution automation solution based on TD-LTE technology in the province of Xinjiang. The results demonstrated that the proposed system is capable of meeting the application requirements.

An Internet-based feeder automation proposal encompassing 3G technology to send IEC 60870-5-104 messages to an overhead line disconnector has been proposed by Jafary *et al.* in [262]. This scenario has been designed with attention to security requirements. Results obtained in the laboratory showed that the solution is capable of preventing access of unauthorized persons, consequently avoiding improper command of disconnectors and making the communication network reliable.

The 5th Generation of mobile networks [16] has revolutionized the design of mobile networks by adding new features and requirements that go beyond conventional voice and data connectivity. 5G networks are being designed to support even higher data rates, low latency applications, and also connectivity to a miscellany of IoT devices. The new generation of the mobile network will provide three different slices [17]. The first one, named as enhanced Mobile Broadband (eMBB), was released in December 2018 and supports up to 20 Gbps of peak data rate in the downlink and 10 Gbps in the uplink. The second slice is called Ultra-Reliable and Low-Latency Communications (URLLC) and it provides less than 10 ms of end-to-end latency. URRLC specifications are expected to be ready in 2020. The third scenario, expected to be standardized in early 2022, is the massive Machine Type Communication (mMTC), which will provide connectivity for IoT devices. Continental size countries, such as Brazil and India, are pushing for a fourth scenario, called enhanced Remote Area Communications (eRAC), which is also expected to be standardized in 2022. In this scenario, the main target is to provide long-range coverage, achieving 50 km while providing 100 Mbps at the edge of the cell [263].

5G networks will provide better support for smart grid applications. The long-range coverage, higher data rates, and low latency will allow the network to be used for monitoring the grid and even capture events during the occurrence of electric failures. Several works in the literature already proposed the use of 4G and 5G networks for smart grid applications.

In [264], Garau *et al.* proposed two strategies for fault control and monitoring in a smart grid. In the first one, it has been proposed centralized management using LTE networks, and in the second one, a decentralized management solution is based on 5G networks. Both have been compared by focusing on the control of power line circuit breakers, evaluating the performance of technologies in the management of energy network failures. For the performance evaluation, a simulation platform that combined the DIgSILENT PowerFactory and OMNeT++ software with the SimuLTE module has been used. An interface possesses been created using Matlab software to provide user interaction with simulation and software management has been developed using a Python script. After the simulations, it has been concluded that 5G technology has characteristics that resulted in a significant improvement in network management performance, reducing decision delays during a failure.

Borenius *et al.* evaluated the limitations of 4G for smart grid management applications and studied the implementation of 5G networks to optimize network management in [265]. In [266], bag *et al.* presented the challenges and opportunities offered by the arrival of 5G technology in smart grid scenarios. In [267], Fang *et al.* evaluated the use of 5G technology for communication with synchronous phasors, taking into account the bandwidth and delay requirements in the communication network. In [268], Leligou *et al.* developed software compatible with 5G, specifically for applications in smart grid scenarios. The software can offer secure and scalable communications.

A novel approach to an AMI application, in which small cells are implemented in the client's domain, has been proposed by Zeinali *et al.* [269]. These cells can manage energy consumption and provide communication for smart meters. This system offered to energy utilities an easier way to migrate to 5G technology. Tests carried out were based on simulations and demonstrated to be promising, pointing to higher coverage when compared to traditional models.

In [270], Saxena *et al.* encompassed small 5G cells for demand response applications. Results demonstrated that the solution offered can reduce the cost of energy produced by up to 30%, providing low latency and acceptable packet loss. In [271], Gross *et al.* evaluated the implementation of an electrical system management software, integrating several microgrids, based on the arrival of 5G technology. In [272], Cosovic *et al.* reviewed the solutions currently offered for distributed state estimation and pointed out how smart grids can benefit from the 5G networks in this scenario.

H. SOFTWARE-DEFINED NETWORKING (SDN)

SDN [18] is a network in which frame forwarding (link-layer frames) is performed through programmable flow tables updated by a central controller implemented in software. Its main objective is to provide flexible and efficient management of networks and devices, regardless of the complexity of the underlying technologies. In the SDN architecture, as illustrated in Figure 3, the control plane is decoupled from the data plane, the network state and intelligence are logically centralized, and the network infrastructure is abstract to applications [273].

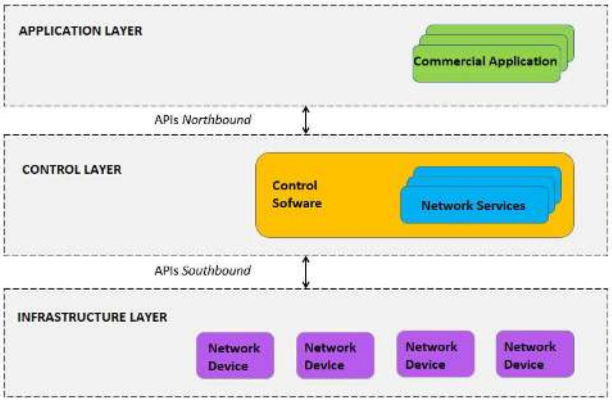

FIGURE 3. Open network foundation (ONF) standardized architecture.

OpenFlow (OF) is one of the most popular proposals for SDN [273]. Software control is limited to configure frame forwarding tables on compatible switches. Frames of unknown streams are routed to the controller where they are analyzed. If a forwarding rule is found, the flow is installed in the switch forwarding table. The OF controller can control tables on physical and/or virtual switches, e.g. Open vSwitch (virtual switch).

In [123], a self-healing Phasor Measurement Units (PMUs) network has been proposed to exploit the dynamic and programmable configuration features of SDN standards for resilience against cyber attacks. After a cyber-attack, the configuration of the network switches is changed to isolate the compromised PMUs and the Phasor Data Concentrator

(PDCs) to prevent attack propagation. Also, disconnected PMUs that are still compromised have been reconnected to the network to ensure network self-healing capability. The solution has been tested on an IEEE 30 bus [274]. It has been concluded that the SDN allows the user to reprogram network switches (Ethernet, for example) in the event of control network failures or attacks, which is critical for mission-critical power network applications.

I. VSAT

The Very Small Aperture Terminal (VSAT) satellite communications system began the operations in the United States in 1981 as small data terminals in corporate networks. Such terminals had the basic feature of customizing the services offered to the customers. VSAT is used by power utility when the distances involved between the control center and the controlled devices are huge or there is no network coverage. Today, most developing standards for 5G do not separate terrestrial from satellite links. That is, the new standards integrate both networks. This is being done in the 3GPP 5G standard. This type of technology has a propagation and processing delay between VSAT stations, which should be considered when sizing for teleprotection services. However, it is a suitable solution for telemetry services for self-healing and reclosing [275]. Also, it is common to use TCP (and other Internet) protocol optimizations to reduce delays. Temporary storage caches are also employed to bring frequent access or delay-sensitive content closer to remote clients.

J. FUTURE INTERNET ARCHITECTURES

Concerned with some limitations of the current Internet stack (TCP/IP and many other protocols), researchers worldwide started to deeply rethink how could a new Internet be designed [21]–[26]. Future Internet architectures (FIAs) have been proposed since 2002 with this aim. The authors of this article have been deeply involved in a FIA proposal called NovaGenesis [23], [276]–[278]. NovaGenesis is founded into four pillars: (i) support for unlimited name spaces and hierarchical name resolution; (ii) everything-as-a-service (XaaS) and protocols-implemented-as-a-service (PIaaS); (iii) name-based and contract driven entities life cycling; and (iv) representatives of physical things (digital twins). NovaGenesis protocols have been designed to take advantage of these features, including self-verifying naming (SVN) employed as identifiers and locators for communicating entities, network caching for contents and name bindings, dynamic and self-organizing protocol layering. With these features, NovaGenesis has been employed for Internet of things [23], [278], content distribution [279], hierarchical name resolution [277] and software-defined networks [278], [280]. NovaGenesis features can be very interesting for mission critical applications, like teleprotection, smart energy, self-healing networks, among others. In fact, NovaGenesis has some similarities with GOOSE concerning the role of semantics in the protocol.

NovaGenesis enables entities to be named in natural and self-verifying (generated by hash functions) languages. Therefore, entities can discover each other and communicate by using their names. Natural language has an important role in this process since services (including protocol implementations) can discover possible peers considering the meaning of their names and keywords. Natural language names (NLNes) are related to SVNes. Name bindings capture relationships among services (e.g. digital twins, protocol implementations, controllers, managers, etc). Such SVNes are employed in packet headers. Thus, the integrity of all communications can be determined. Also, NovaGenesis packets can be routed using labels, similarly to MPLS or KeyFlow [281]. Another feature that can be implemented is virtual circuit creation for communicating services. Digital twins can also be employed to represent and mirror energy distribution equipment, including all components of smart grids, teleprotection networks, substations. Self-organization and contract-based operation are important for future energy distribution scenarios, in which convergence of traditional and decentralized energy generation meet.

Besides NovaGenesis, other architectures such as expressive Internet architecture (XIA) [282], [283] and recursive Internet architecture (RINA) [284] have the potential to be used in telecommunications networks for energy area. XIA defines a novel expressive Internet protocol (XIP) already implemented in the Linux core. XIP enables sending packets using autonomous systems, hosts, services or content identifiers. Therefore, communicating among smart grid services could be achieved by sending packets directly via service names, independently of the host or domain names. RINA is focused on interprocess communication (IPC) via recursive layering. Services communicate one another using their names, based on dynamic layers created bellow. Each layer is formed by IPC processes that have a standardize structure. RINA, XIA and NovaGenesis enable SVNes. These architectures provide intrinsic security and information integrity for communicating smart grid services. Also, digital twins of energy distribution and substation components can be developed as services and communicate directly using SVNes. These features are relevant for mission critical, smart grids, teleprotection, self-healing, etc. Novel architectures can solve old problems and limitations known on current Internet implementation.

VII. CORRELATION AMONG TELECOMMUNICATION TECHNOLOGIES AND TECHNIQUES TO SUPPORT MISSION-CRITICAL AND SMART GRID APPLICATIONS

The search for more efficient, safe, and resilient power grids is based directly on two-way communication among the elements present in the grids (substations, sensors, appliances, among others…), in which they are responsible for the control, monitoring, and performance in the power system. In general, control, monitoring, and actuation techniques can be represented by several smart grids and mission-critical applications, such as Teleprotection, distribution automation, advanced metering infrastructure, substation automation, and distributed energy resources.

In this section, we will initially summarize the key technologies evaluated in previous sections and by surveying works published in the academic field, correlating them with the main mission-critical and smart grid applications. The summary and correlation of available technologies can be seen, respectively, in Tables 1 and 2.

Based on the previous studies, as well as the works evaluated in Table 1, it was possible to observe the current market needs, such as voice-to-data application changes, increased bandwidth demand, and consolidation of a common transport-optimized network infrastructure. Today, it is necessary to migrate SDH/PDH networks for packet switching (Ethernet/IP-MPLS). In addition to the important points mentioned above, it is worth mentioning its decreasing cost compared to the stable cost of legacy networks. The motivation for this change is essential since current SDH/SONET transport networks are connection-oriented and inefficient to handle a larger volume of TDM packets. However, there are some issues to be highlighted when working with an IP/MPLS teleprotection network, such as in applications that require deterministic communications, symmetry requirements in utility applications, default channel routing, lack of supervision channel, and fast protection schemes and its complexity for network configuration and maintenance. This explains why SDH technology has been for a long time popular for mission-critical applications, as it covers some of these limitations due to its effective features, such as real-time communication support, symmetrical delay times, and consequently low jitter, high availability of data channels, and fast routing time.

It can be noted that both circuit and packet technologies have been applied for mission-critical and smart grid applications, like teleprotection network control, AMI, substation automation, distribution automation, and DER. In this context, the highlighted technologies are PDH/SDH, WDM, OTN, EPON/GPON, Ethernet, TCP/IP, MPLS-TP, 3G/4G/5G, RoF, C-RAN, and Fi-Wi. Regarding the telecommunication technologies for control networks, several ones have been explored in this survey, including IEEE C37.218, DNP3, International Electrotechnical Commission (IEC) 60870-5-104, IEC 61850, Modbus, Open Platform Communications (OPC) Unified Architecture (UA). Many of these mission-critical control technologies already embrace packet networks over-circuit or run directly over packet networks.

By evaluating the traditional transport and control network technologies, we suggest the following paths to update mission-critical and smart grid applications:

PDH or SDH Over WDM Control Protocols: It is the traditional path that employs only deterministic circuit switching technologies. Its main advantages are predictable behavior of information flow, OAM support, transparency of transported signals, the resilience of routes, among others. The disadvantage is the cost of operation/maintenance, complexity, and the inflexibility to meet packet network demands.

OTN Over WDM Control Protocols: Similar to traditional deterministic solution, offering similar advantages and disadvantages.

Control Protocols Over TCP/IP/MPLS-TP Over Ethernet: It is an alternative path that adopts statistical packet switching technologies. It allows multiplexing of other traffics on the same network, taking greater advantage of the installed capacities, for instance, to handle voice, data, and video traffics. Therefore, this path supports a flexible network. Requires traffic engineering, especially in route selection, traffic prioritization (through packet scheduling optimization), queue management, selective discard, flow and congestion control, network selection, and admission control functions. Network synchronization is also a requirement at both TCP / IP and Ethernet level. Cost reduction, application flexibility, and complexity reduction are some of the advantages that justify its selection. MPLS-TP improves the required OAM support for control networks.

Control Protocols Directly Over Ethernet: This is an interesting path, which may cost less than TCP/IP with MPLS-TP. Due to this path be a packet technology, it has the same advantages and disadvantages as the MPLS-based path. However, Ethernet has been optimized to support the synchronous and carrier-grade operation. Therefore, this evolutionary path can perform better by reducing overhead when compared to TCP/IP over MPLS-TP over Ethernet.

Control Protocols Over New Network Architectures: With the studies in this article, it was realized the potential of new protocol stacks for use in conjunction with Ethernet, such as the advent of the so-called Future Internet [278]. In [278], the authors adopted the NovaGenesis architecture to integrate, for the first time in the literature, the following ingredients while addressing the emerging problem of dynamic spectrum management in sensor networks and heterogeneous wireless networks, IoT, and Wi-Fi: (i) name-based routing to provide provenance and location-independent access to the control plane; (ii) temporary storage of control data for efficient and cohesive control dissemination as well as asynchronous communication among software controllers and devices; (iii) contract-based control to improve more reliability; (iv) configuration defined by the digital twin services, bringing your settings closer to actual service needs. A proof of concept has been evaluated in a laboratory scenario, demonstrating the approach to automate radio frequency channel optimization in Wi-Fi and IEEE 802.15.4 networks in the 2.4 GHz bands. The work provided a novel control plane implementation for IoT. It has been concluded that the NovaGenesis over Ethernet (preferably synchronous) stack has the potential to be an alternative to existing mission-critical control protocols and may offer similar performance (which needs to be evaluated).

Another fundamental aspect observed is the possibility of integrating circuit and packet solutions in the same network, although this has a higher cost. Of course, legacy interoperability with the new approaches will be the path during migration to more flexible, acceptable performance,

TABLE 1. Summary of the technologies studied and their applications in mission critical and smart grid scenarios.

Telecommunication Technologies	Related work	Typical Applications
Ethernet	[110], [153], [157]–[165]	- Link technology for the communication protocols in the SCADA monitoring system. This system is responsible for communication, monitoring and control of devices located in substations and in the field. - Employed for substation automation through the IEC 61850 standard. - Through the IEC 61850 and IEC 60870-5 standards it provides means for communication between substations and between a substation and the control center respectively. - Transmitting information from smart meters to data collectors and from data collectors to control centers.
PDH/SDH	[188], [189]	- Employed in the utilities legacy systems for teleprotection and remote recloser services. - Communication between substations and between substation and control centers.
WDM/DWDM	[188], [221]–[224]	- Communication between substations and between substations and control centers. - Creation of transparent networks in which various mission-critical signals are exchanged. - Improve applications with PON/GPON/EPON technologies, providing greater bandwidth, security, and protocol transparency when compared to TDM-PON/GPON/EPON.
EPON/GPON	[192]–[199]	- Collect and send data concerning consumption and load balancing in advanced metering infrastructure and demand response applications. - Communication technology for intelligent substations, providing the requirements for substation automation. - Communication between microgrids and control centers in Distributed Energy Resources applications. - The broadband provided by these technologies is also suited to the characteristics of monitoring services using video and/or audio media. - Aggregating traffic from various substations and sending them to control centers. - Act as a bidirectional data path between control centers and remote terminals, to provide real-time network status information.
PoF	[204]–[208]	- Provide power for sensors and other devices located in the power transmission lines safely and reliably, using the electromagnetic immunity characteristic present in the optical fibers and the electrical insulation between the sensors and the power network.
OTN	[213], [215]–[217]	- Act on the power utility core network to support teleprotection traffic. - Interconnecting microgrids with control centers.
Fi-Wi/RoF/C-RAN	[193], [230]–[233]	- Collect and send data concerning consumption and load balancing in advanced metering infrastructure and demand response applications. - Act as a bidirectional data path between control centers and remote terminals, to provide real-time network status information. - Interconnecting microgrids with control centers.
2G/3G/4G	[248]–[262]	- Collecting smart meter data and sending it to data collectors and data centers. - Performing bidirectional data traffic between field-distributed smart devices and control centers. - Acting in connecting remote microgrids to power utility networks and exchanging data between microgrids.
5G	[264]–[272]	- Collect and send data concerning consumption and load balancing in advanced metering infrastructure and demand response applications. - Performing bidirectional data traffic for monitoring and control smart devices distributed in the field. - Acting in connecting remote microgrids to power utility networks and exchanging data between microgrids.
MPLS	[105], [234]–[241], [243], [244]	- Provide communication between substations and between substations and control centers. - Monitoring applications using video and/or audio media. - It is being evaluated in Teleprotection implementations as a replacement to the legacy system used by power utilities. - Performing the exchange of information between the various devices spread across the field, providing various levels of QoS for the services demanded by them. - Virtualization of transport networks through pseudowires, providing redundancy, advanced traffic control, fault management, OAM performance, and security.

and lower-cost technologies. However, future networks that take advantage of packet switching techniques and meet stringent mission-critical requirements should provide better use of installed resources at a lower cost. Decentralization caused by disruptive technologies (such as IoT, microgeneration, Blockchain) requires interoperability of mission-critical control networks. In other words, interoperability of the operator's mission-critical network with microgrids and software platforms from other players. In this context, packet-based technologies seem to be a no-return path, as they are adopted by new entrants in the energy landscape without concern to legacy technologies. Several articles have demonstrated that power operators around the world are migrating their control networks to the packet world using Ethernet and MPLS-TP routes, preferably. Therefore, even if the operator decides not to migrate to packet-based systems, it should interoperate with new entrants in the scenario of microgeneration and decentralized future empowered by recursive technological disruption.

A. OPEN ISSUES

During this research, it has been observed several issues that still require further exploration. The main topics that could be addressed in future studies are:

- Evaluation of the energy scenario with the adoption of new players in the power generation business, surveying the impacts and benefits that will be obtained when a distributed generation scenario is established.
- The development of a testbed for the performance assessment of future Internet architectures in the mission-critical field, especially as an alternative to the

TABLE 2. Correlation of the studied technologies and their applications in mission-critical and smart grid scenarios.

Applications Technologies	AMI	SA	DA	DER	TP
Ethernet	X	X	X		
PDH/SDH			X		X
WDM/DWDM			X		X
EPON/GPON	X	X	X	X	
PoF			X		
OTN				X	X
Fi-Wi/RoF/C-RAN	X		X	X	
2G/3G/4G	X		X	X	
5G	X		X	X	
MPLS	X	X	X		X

Legend:
AMI = Advanced Metering Infrastructure
SA = Substation Automation
DA = Distributed Automation
DER = Distributed Energy Resources
TP = Teleprotection

GOOSE messaging service used in the IEC 61850 standard.

- Evaluation of MPLS variants (MPLS-TP, MPLS-TE and GMPLS) for applications in the energy scenario.
- Implementation of artificial intelligence algorithms for fault detection and recovery in electrical systems.
- Evaluation of emerging technologies to ensure integrity in the data obtained through the application of meter reading, avoiding possible changes in the information along the way performed by this data. An example is the adoption of Blockchain-based solutions. Even alternatives to Blockchain deserve attention, such as the Tangle and HashGraph.
- What virtualization and servitization can do for energy grids? 5G, IoT, SDN and network function virtualization (NFV) [285] are emerging paradigms that offer flexibility, elasticity and programability of network resources for future smart grids. These techniques are supporting the changes in 5G, and can therefore be the differential for the grids of the future.
- Another opportunity is the evaluation of future Internet architectures regarding mission critical and control networks. Research projects like NovaGenesis, XIA and RINA could have useful features to address future smart grids, self-healing and teleprotection networks. To the best of our knowledge, there is no research on this area. Expressiveness, self-verifying naming and semantic rich orchestration can contribute for more robust and self-organizing computers networks for the energy sector. An opportunity for novel investigations.

VIII. CONCLUSION

The communication network is a vital part of the mission-critical system in a power grid. With the popularization of packet-based technologies and their mass usage in the various technological fields, it was expected that dealers would revise their legacy systems, already based on deterministic technologies, seeking a gradual migration to dynamic technologies, such as MPLS and IP. In this article, we emphasize possible communication technologies that could meet the requirements of utilities in the power transmission and distribution sectors and Smart Grids evolution.

With this survey, we observed the possibility of integrating circuit and packet technologies in the same network, in order to preserve the investments made by the power utilities. The gradual migration from the legacy network to packet technologies has also been observed, mainly due to the fact that applications that are emerging with smart grid concepts are already being developed in packet-based technologies. Combined with the factors highlighted above, we are facing the end of the life cycle of legacy TDM technologies. We also noted that decentralization caused by disruptive technologies (such as IoT, microgeneration, Blockchain, etc.) requires the interoperability of mission-critical control networks. In other words, interoperability of the operator's mission-critical network with microgrids and software platforms from other players. Therefore, even if energy operators decide not to migrate to packet technologies, they should interoperate with new entrants in the scenario of microgeneration and decentralization empowered by recursive technological disruption. The convergence of technologies discussed in this article leads to the creation of dynamic energy markets based on TCP/IP/MPLS, Ethernet, IoT, 5G, and Blockchains. A very dynamic world is better supported by packet switching technologies.

The initiative for the evolution of communication networks in energy utilities can already be seen in several countries, but in Brazil, the migration process still occurs slowly. In this context, the study presented in this article is part of a D0640 project, funded by the Brazilian company CEMIG in partnership with the Agência Nacional de Energia Elétrica (ANEEL), in charge of evaluating possible communication technologies for future operative data networks. This project covers the scenarios of supervision, control, and protection of the power network, aiming to identify the feasibility, performance, impacts, and benefits of adopting packet-based technologies in the CEMIG's mission-critical distribution network, in particular those who refer to the teleprotection scenario.

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