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Communication Technologies for the Smart Grid - A Short Review and a Case-Study Analysis

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Abstract. The rapid development of power systems requires an advancement of smart grids, to enable a more efficient management of power generation, distribution, and consumption, as well as an integration of a greater number of renewable energy sources. The key role in the functioning of these systems is played by the communication infrastructure which ensures a reliable, interoperable, and scalable data exchange across all levels of the network, from the end users to the central control system. The paper provides an overview of the modern communication technologies used in smart grids and analyzes their characteristics and application across the HAN, NAN, FAN, and WAN layers, and ultimately, the storage of the power network data to predict various variables related to the power consumption management, power system control, etc. A special emphasis is placed on selecting optimal technologies in accordance with the current infrastructural capabilities and technical requirements. It discusses a potential application of the communication technologies in future smart grids. Results for a segment of a real-world power system are presented, including measurements of photovoltaic power plant production and consumption, implemented communication technologies, and available data. The research results highlight the importance of choosing appropriate communication technologies for future smart grids. The data which is available, accessible, scattered across different databases can serve as a solid foundation for a significant improvement of the existing power systems.

Keywords: smart grid, communication technologies, communication networks architectures, AI techniques

Komunikacijske tehnologije za pametna omrežja – kratek pregled in študija primera

Razvoj elektroenergetskih sistemov zahteva napredna pametna omrežja za učinkovitejše upravljanje energije in vključevanje obnovljivih virov. Ključno vlogo ima komunikacijska infrastruktura, ki omogoča zanesljivo in razširljivo izmenjavo podatkov med uporabniki in nadzornim sistemom. Prispevek podaja pregled sodobnih komunikacijskih tehnologij za pametna omrežja ter njihovo uporabo na ravneh HAN, NAN, FAN in WAN. Analizira se tudi shranjevanje podatkov za napovedovanje porabe in nadzor sistema, pri čemer je poudarek na izbiri tehnologij glede na tehnične zmožnosti. Predstavljena je študija primera dejanskega sistema s podatki o proizvodnji in porabi fotonapetostne elektrarne ter uporabljenih tehnologijah. Rezultati poudarjajo pomen pravilne izbire komunikacijskih rešitev za prihodnji razvoj pametnih omrežij.

1 INTRODUCTION

Smart grids represent a key innovation in modern power systems, enabling a more efficient management of the power production, distribution, and consumption. The foundation of the system lies in a complex communication infrastructure that facilitates the exchange of information between a large number of distributed devices and central control systems. One of the biggest challenges in the development of the smart grids is establishing an efficient and secure bidirectional communication system that enables monitoring and control of all network layers - from consumers to distributors and system operators. Communication technologies in smart grids can be either wired or wireless, and their selection depends on various factors such as the terrain topography, technical and operational requirements, existing infrastructure, and the cost of implementing future technologies. To ensure scalability, security, interoperability, and low latency, the communication infrastructure of smart grids is organized in a hierarchical structure. It is important to have the network data stored on a cloud platform for the purpose of analyzing and managing the power system with an appropriate use of the AI techniques.

The importance of the above challenges is further confirmed by the growing number of the scientific literature addressing the analysis and application of the communication technologies in low-voltage smart grids.

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The total number of publications in three databases (IEEE Xplore, Science Direct, and Springer Nature) that search the topic using the term ‘Communication technologies in low-voltage smart grid’, is presented in Fig. 1. It is shown that the researchers’ interest in the topic has been steadily increasing over the past decade. The research highlights the interdisciplinary nature of the area and its significance in the domains of power engineering, information technology, and automation.

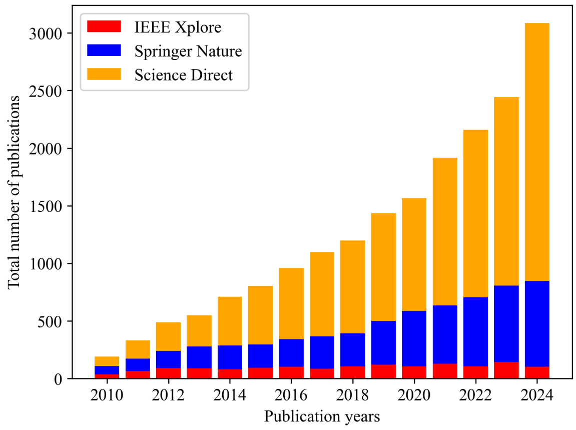

Figure 1. Total number of publications in three databases searched as ’Communication technologies in low-voltage smart grid’.

The increased demand for the electricity, the wider application of renewable energy sources, and the need for a stable and secure power supply require an advanced infrastructure to enable real-time monitoring, management, and data analysis. By researching the existing infrastructures and understanding the significance of smart grids, a need has emerged for developing communication technologies that enable a reliable data transmission across different layers of the smart grid. Contributions to the development of more efficient and resilient systems enable a greater transparency in the power distribution and provide the basic foundation for introducing new services and applications for energy management. Considering various smart grid applications such as Monitoring and Optimization, Smart Grid Security and Cybersecurity, Advanced Metering and Smart Infrastructure, and Next-Generation Smart Grid Technologies, the paper presents an overview of the communication technologies used in smart grids, with a focus on their application across all layers of the hierarchy. A special emphasis is placed on selecting optimal technologies in accordance with the specific characteristics of the given infrastructure, or the needs and capabilities of a specific network layer. The paper is organized as follows. Chapter 2 reviews the literature about the communication technologies that enables an efficient bidirectional communication between utilities and consumers, facilitating real-time monitoring, automation, and optimization of power distribution. Chapter 3 discusses the communication technologies in smart grids, with a special focus on the existing network infrastructure and an appropriate selection of technologies for each network layer, including a presentation of selected measurement results from a real low-voltage network. Chapter 4 draws conclusions.

2 Literature Review

Integrating advanced communication technologies in smart grids is a serious technical, operational, and regulatory challenge. These technologies enable an efficient two-way communication between utilities and consumers, facilitating a real-time monitoring, automation, and power distribution optimization. Recent studies underscore the importance of the digital infrastructure, such as advanced metering infrastructure, blockchain, and edge computing, in achieving decentralized decision-making and more responsive power [1], [2].

Smart grids (SG) rely on robust communication networks to manage the complexities of modern power systems [3]. Wireless IoT technologies [4] are revolutionizing smart grid automation, with ZigBee, Long-Term Evolution (LTE), Low-Power Wide-Area Network (LPWAN), and Worldwide Interoperability For Microwave Access (WiMAX) optimizing Home, Neighborhood, and Wide-Area Networks (HANs, NANs, WANs) for bidirectional energy flows, predictive maintenance, and secure data exchange [5]–[8]. Integrating automation and advanced data analytics within these networks strengthens the power grid sustainability, reliability, and efficiency [9]. Artificial Intelligence (AI)-driven solutions embedded within the Internet of Things (IoT) protocols have demonstrated their potential to enhance the power forecasting accuracy and reinforce the security of the distributed power management [10]–[12]. Advanced machine learning models, fuzzy logic controllers, and AI-driven optimization improve the grid efficiency, minimize the power losses, and support adaptive demand-side response strategies [13], [14]. Neural networks and other machine learning techniques further refine the power consumption forecasts, leveraging the large datasets generated by smart meters [10]. Moreover, the advanced sensor integration enhances the system automation and enables an effective anomaly detection [15]. It has been shown that the hybrid communication models combining the Power Line Communication (PLC) with wireless technologies enhance the power grid reliability and real-time monitoring [16]. So, it can be concluded that innovations in the Advanced Metering Infrastructure (AMI), Distributed Control Systems (DCS), and SCADA enhance the power grid adaptability and automation [17], [18].

Effective power demand response mechanisms depend on the reliability of communication protocols, allowing consumers to adjust their power consumption based on real-time pricing signals [19]. These strategies optimize the power distribution by dynamically aligning the power demand with the available power generation capacity. Prosumers benefit from the ability to actively participate in energy markets, leveraging advanced communication technologies to synchronize their production and consumption patterns [20]. Also, advanced ICT solutions facilitate seamless Renewable Energy Sources (RES) integration, ensuring the grid stability and efficiency within an increasing penetration of renewables [21].

IoT-assisted smart grids enhance real-time monitoring and interoperability using cloud-based and web-based models. Scalable protocols like Message Queuing Telemetry Transport (MQTT), Constrained Application Protocol (CoAP), and Open Platform Communications United Architecture (OPC UA) optimize the data exchange across heterogeneous grid components [22]. Enhancing the smart grid interoperability, Interoperable Smart Microgrids (ISMs) optimize local power exchanges, reducing the reliance on central grids. Long Range Wide Area (LoRa)-based wireless communication is emerging as a low-power, long-range solution for real-time smart grid monitoring and power distribution optimization. Its ability to support millions of nodes with a minimal latency enhances the scalability and efficiency of decentralized power networks [23], [24]. Urban power systems in smart cities are evolving through IoT, 5G/6G, AI, and blockchain for a real-time power optimization and adaptive management. Smart grids, zero-emission buildings, and renewable-powered public transport are the key to reducing carbon footprints and enhancing sustainability [25]. Micro and nano-grids are advancing a localized power autonomy by integrating solar, wind, and power storage technologies. Smart control mechanisms, blockchain-enabled transactive energy systems, and quantum cryptography are emerging to enhance the security, efficiency, and real-time grid optimization [56]. Ensuring a secure and low-latency communication in decentralized power networks relies on standardized frameworks, where protocols, such as IEC 61850 and IEEE C37.118, are facilitating interoperability, enhancing cybersecurity, and enabling a real-time grid control, optimizing the efficiency and resilience of modern smart grids [45]. Cyber-Physical Systems (CPS) in smart grids integrate real-time sensing, control, and computational intelligence, ensuring resilience and efficiency. Communication networks are central to secure the data exchange, fault detection, and automated grid response, aligning with the evolving SG-CPS standards and interoperability frameworks [57]. Advancements in smart grid telecommunication highlight the role of Wireless Sensor Networks (WSNs) and emerging protocols in energy management.

Technologies such as GPRS, PLCC, Wi-Fi, ZigBee, GSM, and 3G/4G/5G enhance the grid stability, reduce the latency, and improve the power dispatch [26], [41]. The 5G and 6G technologies enable an ultra-reliable, low-latency connectivity for distributed power resources [49]. LTE-based metering infrastructures further address the scalability and security challenges [27]. Integrating the ZigBee and MapX technologies enhances real-time fault detection in smart grids by establishing sensor networks for monitoring and optimizing fault localization. The RBF-PCA-WFCM clustering algorithm further improves the diagnostic accuracy and reduce false and missing alarms [28]. Comparative analyses of the IEEE 802.15.4g, LoRa, and LTE in NANs demonstrate their efficiency in packet delivery and latency reduction. Simulations using ns-3 and OMNeT++ confirm their role in mitigating network congestion and optimizing the data exchange [60].

Despite advancements, significant challenges persist in the smart grid communication technology integration and implementation. Hybrid power management models integrating RES rely on robust communication infrastructures to balance the power generation and consumption effectively [68] Similarly, vehicle-to-grid (V2G) technologies introduce additional complexities in the power exchange, necessitating advanced communication systems to manage interactions efficiently [29]. Infrastructure limitations pose barriers to smart meter adoption and consumer power behavior management [63]. Communication failures impact the state estimation accuracy, necessitating improvements in the reliability and fault tolerance [30]. The scalability of SG is another concern, with the growing number of distributed power resources adding complexity to the system management. Interoperability between diverse technologies, including IoT, 5G, and blockchain, presents opportunities and integration challenges, necessitating cohesive frameworks for a seamless operation [64]. Furthermore, integrating AI-driven solutions with the existing grid infrastructure requires overcoming the interoperability and scalability issues, ensuring a seamless operation across legacy and modern systems [50].

However, persistent obstacles, including cybersecurity risks, privacy concerns, and policy gaps, must be addressed to facilitate a seamless RES adoption [69]. The ongoing research focuses on improving the communication networks, refining demand-side management algorithms, and tackling integration challenges to build a more resilient and sustainable energy future. The advancement of smart grid communication and control architectures is fundamental to the future of power systems, with next-generation frameworks to enhance a high-speed data exchange, predictive analytics, and

Table 1. Overview of Communication Technologies in Smart Grids

Communication Technology		Reference
Wireless Communication Technologies	• 5G, 6G/B6G, LTE, WiFi, LPWAN (LoRa, Sigfox, NB-IoT) • ZigBee, WLAN, WiMAX, Bluetooth, GSM (3G, 4G, 5G) • 3GPP LTE, Non-Terrestrial Networks (NTN) • Machine-to-Machine (M2M) Communication, Cognitive Radio • Wireless Power Transfer (WPT), V2G	[1], [2], [5], [8], [19], [23]–[40]
Wired Communication Technologies	• Optical Fiber, Broadband over Power Lines (BPL), Digital subscriber line (DSL) • (PLC), Narrowband Power Line Communication (NB-PLC)	[16], [26], [41]–[44]
Internet of Things (IoT) and Edge Computing	• IoT, Industrial IoT (IIoT), Smart Meters, AMI • IoT Protocols (CoAP, MQTT, XMPP, DDS, AMQP) • Multi-Agent Systems (MAS), Smart Grid Automation • Multi-source Heterogeneous Data Fusion, Edge Computing • WSN, Demand Response Management (DRM)	[1], [3], [4], [14], [20]–[22], [38], [40], [45]–[48]
Artificial Intelligence (AI) and Machine Learning	• AI, Machine Learning (ML), Deep Learning, Reinforcement Learning (ANN, SVM) • AI-Driven Optimization, Embedded Systems • Federated Learning (FL), AI for Renewable Energy Integration	[2], [10], [13], [15], [17], [49]–[55]
Cybersecurity	• Blockchain, AI, IoT for Transactive Energy Systems • Quantum Cryptography, CPS • Identity-Based Encryption (IBE), Public Key Infrastructure (PKI) • Cybersecurity, Data Privacy	[15], [49], [50], [52]–[54], [56]–[59]
Smart Grid Standards and Protocols	• IEC 61850, DNP3, MMS, XMPP • Open Communication, QoS, Software Defined Networking (SDN) • HAN, NAN, WAN	[6], [7], [12], [20], [60]–[62]
Advanced Metering and Demand Response Technologies	• AMI, Demand Side Management (DSM) • Smart Inverters, Distributed Energy Resources (DER), Predictive maintenance • Smart Grid-Powered Wireless Communication, IoE	[3], [7], [9], [11], [17], [18], [21], [63]–[67]

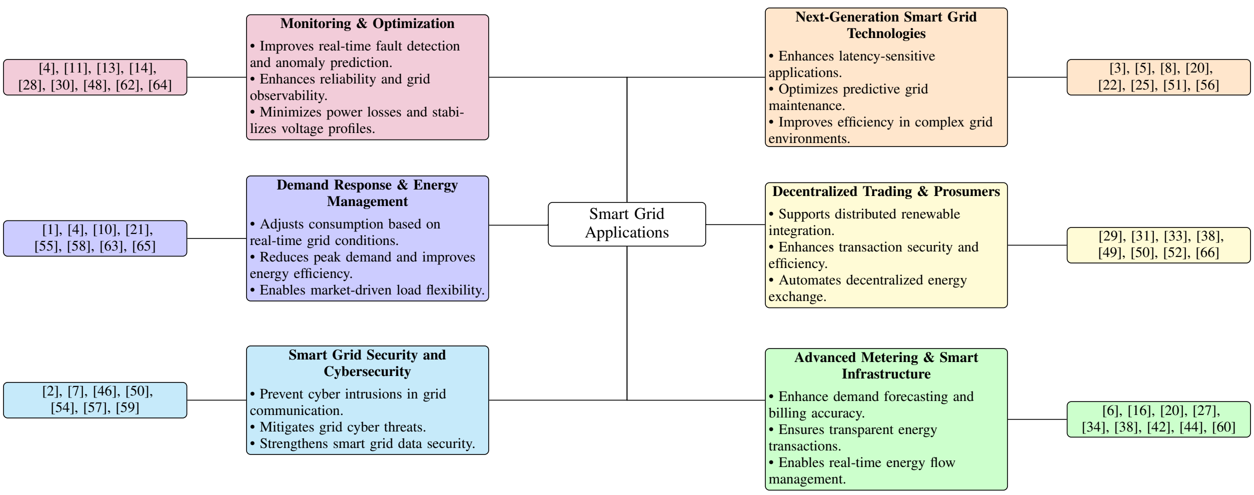

Figure 2. Overview of Smart Grid Applications

fault-tolerant operation [51]. The future research should focus on enhancing security measures, ensuring interoperability across heterogeneous devices, and leveraging the next-generation communication technologies, such as 6G, to overcome the existing constraints [19], [70]. The below table presents an overview of the communication technologies relevant to smart grids, including wireless and wired communication methods, IoT and edge computing, artificial intelligence applications, cybersecurity measures, smart grid standards, and advanced metering technologies.

Table 1 presents an overview of the communication technologies relevant to smart grids, including wireless and wired communication methods, IoT and edge computing, artificial intelligence applications, cybersecurity measures, smart grid standards, and advanced metering technologies. Fig. 2 provides a categorized overview of the key smart grid applications, highlighting advancements in monitoring, optimization, demand response, cybersecurity, next- generation technologies, decentralized trading, and metering infrastructure.

3 An Analysis of Communication Technologies in Smart Grids Based on the Network Hierarchy of Real-World Power Systems

In smart grids, communication technologies are structured in a hierarchical manner, beginning at the level of end-users and progressing toward centralized cloud-based data storage systems, thus facilitating an effective control of power systems. The communication technologies used in smart grids can be either wired or wireless, with most power systems utilizing a combination of different wired and wireless technologies, depending on the existing infrastructure. When selecting a communication technology for smart grids, several factors must be considered, including the geographical topology, technical and operational requirements, and implementation costs. In this regard, the wireless communication has a lower costs and a simpler implementation, whereas the wired communication is less susceptible to interferences.

The general scheme in Fig. 3 illustrates the main network domains which differ according to the coverage area and data rate. The local networks operate at lower data rates (in the range of kbps), whereas the Wide Area Networks (WANs) support significantly higher rates (up to 1 Gbps). The coverage increases from Home Area Networks (HAN) towards WANs: HAN networks cover small areas (e.g., individual households), while WANs span large geographic regions such as cities and entire regions. HAN/BAN/IAN represent local domains with a typical range of 1 to 100 meters and data rates between 10 and 100 kbps. A key component of these domains are smart meters, which collect the data on the power consumption and transmit it to utility operators, thereby enabling an analysis of the consumer behavior and the provision of personalized services. These networks are connected to a Neighborhood Area Network (NAN) gateway, which transmits the data to higher levels of the communication infrastructure. NANs cover the areas

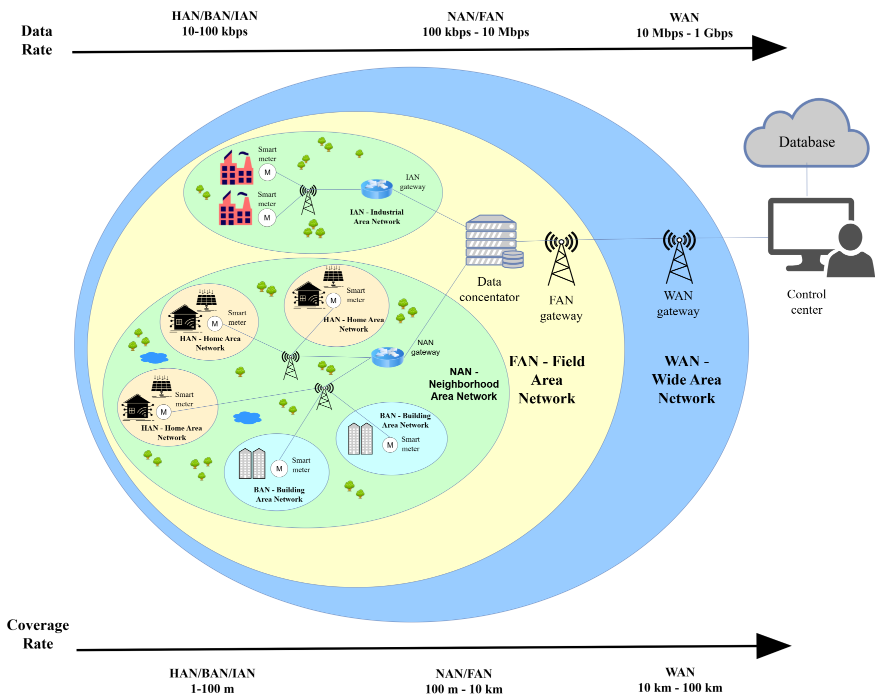

Figure 3. Communication Networks in Smart Grids: Coverage and Data Rate Hierarchy.

ranging from 100 meters to 10 kilometers, with the data rates between 100 kbps and 10 Mbps. They aggregate the data from multiple HAN/BAN/IAN networks and forward it via the NAN gateway to centralized systems. The NAN gateway communicates with smart meters and transfers the collected data to the Field Area Network (FAN). FANs, with a similar coverage range (100 meters to 10 kilometers) and the data rate (100 kbps to 10 Mbps), are responsible for connecting the NAN gateways with utility operators. A Data Concentrator collects the data from several NANs and relays it to WAN through a FAN gateway. WAN facilitates the data transmission between the FAN network and the central control system of the utility provider. The WAN gateways provide access to a central database and control center. The data collected through the hierarchical layers of the communication infrastructure is stored in a centralized cloud-based database, which supports the data analysis, resource optimization, and power management. Data storage platforms employ advanced Artificial Intelligence (AI) and Machine Learning (ML) algorithms to optimize the power consumption, predict failures, and enhance the overall efficiency of the power grid.

Conversely, Fig. 4 illustrates a single-line diagram representing a segment of an actual low-voltage power system. The system from the primary transformer substation supplies a 10/0.4 kV transformer substation of rated power of 250 kVA, via a 10 kV distribution line. On the low-voltage side, the photovoltaic power plant $\mathrm{P_{PV2}}$, with a capacity of 90 kW, is connected via XP00-A 4×150 mm^2 and NAYY 4×95 mm^2 cables. The power plant is directly connected to a 0.4 kV low-voltage grid. Metering point $\mathrm{MP_1}$ is the location where the local power distribution company, using a high-accuracy class multifunction meter, measures both the power delivered to and consumed from the power plant. The metering point serves as an official reference for power billing. Fig. 5 shows the power production of $\mathrm{P_{PV2}}$ (G_2) for the month of February 2025. The measurement results indicate that the daily power production varies depending on weather conditions. The data transfer from $\mathrm{MP1}$ is carried out either through a manual meter reading or via a GSM communication. On the other hand, connected to the low-voltage line marked as '2' in the diagram is a metal processing factory which has a rooftop photovoltaic power plant with a capacity of 90 kW. Power plant P_{PV1} is intended for self-consumption and does not feed the power into the grid. The factory and its power plant are connected to a transformer substation via an XP00-A 4x95 mm^2 cable. Fig. 6 presents the power consumption of this facility, measured at $\mathrm{MP2}$, as well as the production of $\mathrm{P_{PV1}}$ during February 2025. The figure shows that $\mathrm{P_{PV1}}$ (G_1) exhibits lower production values compared to $\mathrm{P_{PV2}}$ (G_2), which is a consequence of the power limitation conditioned by the consumption level. Total power consumption $\mathrm{PL_1}$ is the sum of the power measured at $\mathrm{MP2}$ and the production of $\mathrm{P_{PV1}}$. Metering point $\mathrm{MP_2}$ is also owned by the local power distribution company and is equipped with a high-accuracy class multifunction meter. The low-voltage line labeled as '3' in the diagram represents other local power consumers.

Metering points $\mathrm{MP_3}$ and $\mathrm{MP_4}$ correspond to the measurements of the power plants and local power consumption, respectively. The data from these points are owned by the investor. The local power distribution company has no access to this information. These measurements constitute the monitoring system of the power plants, where the metering devices (Power Sensor, Logger, and Inverters) are interconnected via CAT 6 communication cables using the RS485 protocol. Investors have access to the data through the appropriate software platform provided by the inverter manufacturer. The available data from these measurements are presented in a form of minute-based, 15-minute, hourly, and monthly reports. The available parameters include: AB line voltage (V), Active power (W), BC line voltage (V), CA line voltage (V), Current/Phase A current(A), Negative active power (kWh), Negative reactive power ($kvarh$), Phase A voltage (V), Phase A active power (W), Phase B active power (W), Phase B current (A), Phase B voltage (V), Phase C active power (W), Phase C current (A), Phase C voltage (V), Positive active power (kWh), Positive reactive power ($kvarh$), Power factor, Reactive power (var) and Total apparent power (kVA).

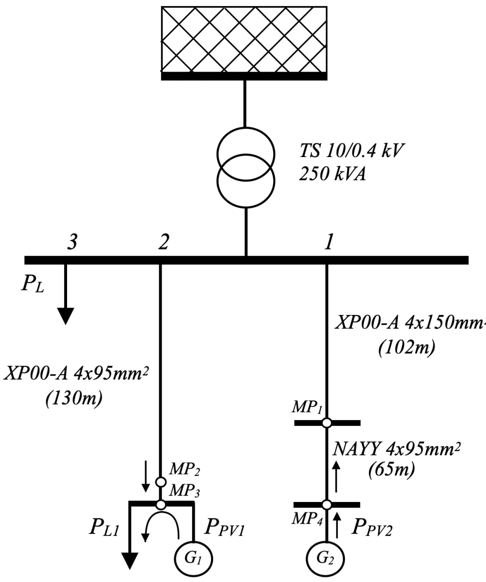

Figure 4. Single-line diagram of a part of a real low-voltage system.

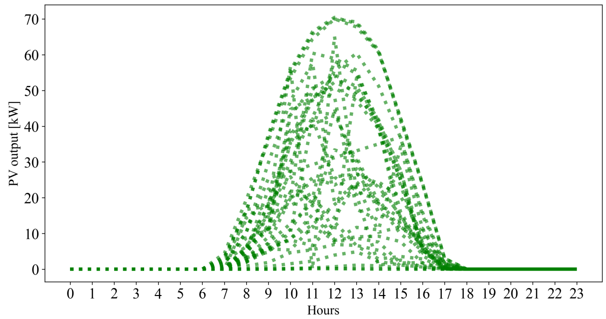

Figure 5. Powerflow results for P_{PV2}.

Figure 6. Powerflow results for P_{PV1}.

One of the most important aspects of smart grids is the implementation of advanced communication technologies that enable data acquisition about the network and system management. The DEEO (Distribution Power System Components) system serves as a primary data source for the power distribution system (facilities, network, equipment) for other systems and applications used in the power distribution. Besides the components shown in Fig. 4, it consists also [71]:

- Technical and spatial database of the power distribution system facilities and equipment,
- GIS component,
- WEB component (DEEO application).

The data can be viewed and updated via web and desktop applications. The web application updates only the technical data, whereas the desktop application updates both the technical and the spatial data. Both applications communicate with the database through the web services. They are specifically developed for the needs of a competent power distribution system operator. The underlying database is a standard Oracle database.

With the integration of advanced technologies and applications to achieve a smarter power grid infrastructure, a massive amount of the data is generated from various applications for a further analysis, control, and real-time pricing methods [72]. This requires a bidirectional communication and interoperability between a large number of power distribution operators and system control applications. For a smart low-voltage grid where all the consumer data is uploaded to a central cloud-based platform, the choice of the communication technology depends on factors such as the availability of the existing infrastructure, population density, specific needs of individual network layers, reliability, latency, security, and scalability. The use of ZigBee, Wi-Fi, LoRaWAN, NB-IoT, 4G LTE, optical and 5G networks, combined with advanced AI techniques for the data analysis—including machine learning—enables a future optimization of the grid operation, prediction of network failures, and forecasting the power consumption and demand for an efficient management of the renewable energy sources.

In general, the smart grid infrastructure is divided into three main communication network architectures: Home Area Network (HAN), Neighborhood Area Network (NAN), and Wide Area Network (WAN) [6]. Their detailed overview is provided below, with respect to their implementation and integration into real-world power systems within smart grids. HAN is the smallest unit in smart grids and is primarily used in residential environments, serving as a communication infrastructure for sensors and devices within households. HAN connects smart appliances, smart meters, home energy systems (e.g., solar panels, smart thermostats), and other IoT devices that enable optimization of the power consumption. Communication at this level is most commonly achieved using Wi-Fi, ZigBee, Bluetooth, and Power Line Communication (PLC) technologies due to their widespread adoption and low power consumption. Wi-Fi is most commonly used for the data aggregation in smart homes before forwarding to the cloud. ZigBee is suitable for Home Power Management Systems (HEMS). PLC uses electric wiring to transmit the data, providing a high throughput and a low latency, making it suitable for communication in densely populated smart grid environments [73]. It is also suitable for an in-house communication between smart meters and local controllers. IAN encompasses industrial and manufacturing complexes with specific requirements for a secure and low-latency communication. It utilizes 5G, LoRaWAN, private LTE, SCADA, OPC-UA, and Modbus protocols to connect large facilities with power management systems. It enables a precise control of the power consumption and production in industrial zones, thus contributing to a grid optimization. SCADA (Supervisory Control and Data Acquisition) systems allow real-time monitoring and control of the grid by acquiring the sensor data to balance loads and manage faults. BAN utilizes PLC, LoRaWAN, and NB-IoT, as well as Ethernet in buildings with an existing network infrastructure. In the above networks, smart meters collect the data and relay it to utility data centers via NAN which connects smart meters and various utility devices, including switches, reclosers, line sensors, bank capacitors, electric vehicle charging stations, and battery storage systems [60]. NANs cover a wider geographical area compared to HANs and BANs and play a crucial role in data transmission. This layer commonly uses NB-IoT, LoRaWAN, WiMAX, LTE-M, and RF Mesh technologies, enabling data aggregation from multiple households or buildings and distribution to centralized energy management systems. The NB-IoT and LoRaWAN technologies are suitable due to their power efficiency and capability to cover larger urban areas with no significant need for an additional infrastructure. For the FAN layer, the implementation of 4G LTE and fiber optics is recommended in densely populated areas, while WiMAX and radio networks can be used in wider and less accessible regions. These technologies provide a reliable, low-latency communication, which is essential for the integration of renewable energy sources and grid automation. Finally, the WAN represents the broadest layer of the smart grid communication infrastructure, connecting FAN networks with centralized analytics and decision-making systems. WAN links data collectors to utility control centers, ensuring a seamless communication across the smart grid. For a long-distance data transmission, cellular communication technologies have primarily been used. 2G, 2.5G, 3G, and LTE are the cellular communication technologies available to utilities for smart metering deployments. When a typical data transfer interval of 15 minutes between the meter and the utility is used, a substantial amount of the data is generated, requiring a high data rate connection to transfer the data to the utility [18], [74]. To achieve higher speeds, modern implementations at this layer increasingly rely on 5G, optical networks, satellite communication, and SD-WAN technologies for long-distance data transmission, enabling a centralized grid management. For the WAN layer, the use of optical networks is recommended as the main communication backbone between regions, with a 5G support in urban centers to improve the speed and reduce the latency. On the other hand, optical fibers are also used for monitoring and control within WAN and for connecting substations to control centers. The advantages of optical fibers are a long-distance transmission capability, high bandwidth, and resistance to electromagnetic interference [26]. However, their main drawbacks are a high cost and a limited number of access points. Besides the optical fibers, Ethernet can also be used for communication between substations and control centers.

Following the above, it is evident that establishing a bidirectional communication between generation units, distribution operators, and end consumers enables not only an improved control and management of electricity consumption, but also an alignment with the current demands of the electricity market. Therefore, a further development and enhancement of such systems—particularly in the context of digitalization and integration of renewable energy sources—represents a key step toward an energy-sustainable future. As demonstrated in the segment of a real-world power system, communication technologies have been implemented and the data is available. However, the public utility companies are developing these systems primarily for their own operational needs, while other highly valuable data largely remains underutilized.

4 Conclusion

The paper continues the research presented in [75]. It provides a brief overview of the communication technologies expected to be utilized in future smart power grids. When planning the implementation of a smart power grid, the choice of the communication technologies should be based on the availability of the existing infrastructure, population density, and specific needs of individual network layers. The use of ZigBee, Wi-Fi, LoRaWAN, NB-IoT, 4G LTE, optical and 5G networks, along with advanced cloud data storage solutions, enables a reliable, efficient, and scalable energy infrastructure aligned with modern smart city standards.

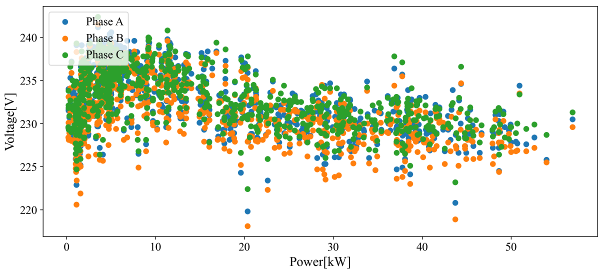

Figure 7. Voltage versus power relationships measured in MP_3.

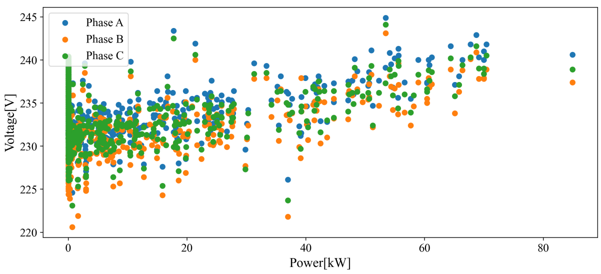

Figure 8. Voltage versus power relationships measured in MP_4.

On the other hand, using a part of a real power system as an example, it is shown that there is a large amount of highly relevant data available for planning, operation, and management of the power distribution system, but this data is not centralized. For instance, Figures 7 and 8 show the voltage variation as a function of the power variation for points MP_3 and MP_4 from Fig. 4.

Fig. 7 shows the voltage variation as a function of the consumption power. It can be concluded that as the power increases, the voltage levels decrease, but still remain within the acceptable limits. On the other hand, Fig. 8 illustrates the voltage variations as a function of the variations in the generated power from a photovoltaic power plant, and it can be concluded that with an increased generation from P_{PV2}, the voltages in the network increase, yet they remain within the permissible limits. Unfortunately, such highly important information about the network voltage levels is for the analyzed case not available to the responsible system operator which hinders a faster development of an advanced system.

The above analysis confirms the importance of appropriately selected communication technologies in smart power grids. By implementing communication solutions, it is possible to enhance the operational efficiency, increase the grid security, and improve the management of the power consumption and production. The development of smart power grids requires a continuous research and technological adaptation, especially in the context of the increasing presence of distributed power sources, digitalization, and urbanization. Through a combination of the communication infrastructure, cloud platforms, and artificial intelligence, it is possible to achieve a highly adaptive and sustainable power grid ready to face future challenges. Finally, as demonstrated with the case of the part of a real power system, communication technologies are available, appropriate measurements and databases exist, and very precise data on the power distribution system is accessible. However, improving the most power grid and enabling new services requires an additional effort and the development of new software solutions.

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