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Review

Comprehensive Review of Renewable Energy Communication Modeling for Smart Systems

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Abstract: Due to the rising trends in the adoption of smart systems such as smart grids, smart homes, and vehicle-to-grid, there has been a lot of research interest in these areas. To manage these complex systems effectively and intelligently, a reliable, high-speed, and secure data communication network is very essential. The key distinguishing feature between smart systems and traditional ones is that smart systems use a two-way communication system while traditional systems usually use one-way communication. The requirements and techniques needed to ensure safe, secure, and reliable communication in smart systems have been the focus of many researchers in recent times. This work is aimed at providing a comprehensive, all-encompassing, up-to-date review of smart systems communication to ascertain the research directions as well as challenges. This review will guide other researchers in delving into smart systems communication to identify potential research problems and future research directions or research gaps.

Keywords: communication; smart systems protection; smart grid; smart homes; virtual power plants

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1. Introduction

Sequel to the worsening energy crisis and rising environmental pollution, developing and utilizing renewable energy resources has become an unavoidable option for ensuring a secure and long-term energy supply. In recent years, installed capacities of renewable energy systems have increased, changing the power generation sources of power systems, which are dominated by fossil fuels to a high percentage of renewable energy sources [1]. As the modern intelligent grid/future electrical power systems rely substantially on the efficiency of the underlying communication infrastructure, traditional power distribution networks are rapidly transitioning to modern (smart) grids. The smart grid ecosystem is designed to enable high-demand real-time applications, such as electric vehicles, and balancing demand and supply in smart cities, and its general architecture includes distributed renewable energy sources (DRESs). As a result, in both industrialized and developing countries, there is a growing trend toward integrating DRESs into presently established energy networks. Nonetheless, integrating DRESs creates a highly scattered environment, which poses several issues in terms of real-time communication between smart grid operational layers and smart city applications [2] Power grid architecture and management are changing as a result of the incorporation of non-grid assets such as rooftop photovoltaics, microgeneration capabilities, battery storage, combined heat and power, electric vehicles, and other types of distributed energy resources in the distribution sphere [3]. The importance of renewable energy communication in the future grid (smart grid) cannot be overemphasized. Smart grid technology connects renewable energy sources to the electricity system and allows for efficient control and distribution. Utilities can use the Internet of Things (IoT) to collect data on the smart grid and use constant self-assessments to promptly remedy concerns. The smart grid and renewable energy have a relationship that revolves around data collection. These data are then rapidly delivered to the grid to alert the utility of any concerns, which enhances both service quality and safety [4].

Smart grids monitor, manage, and control electricity to fulfill the various requirements of their customers by utilizing artificial intelligence, digital technology, and cutting-edge communication strategies. Specifically, smart grids can coordinate the requirements and capacities of all market participants to ensure that every aspect of the system functions efficiently, reducing both financial and environmental costs while simultaneously maximizing the stability and dependability of the services offered [5,6]. In this context, integrating an effective, trustworthy, and interoperable communication system is necessary for the design and execution of a secure and economical electricity supply network [7].

Figure 1 depicts the communication infrastructure for distributed energy resources (DER). From a communication standpoint, DER networks can be categorized into three strands; first, primary controller to secondary controller communication, second, secondary controller to central supervisory control, and finally, central supervisory controller to other DER systems [8].

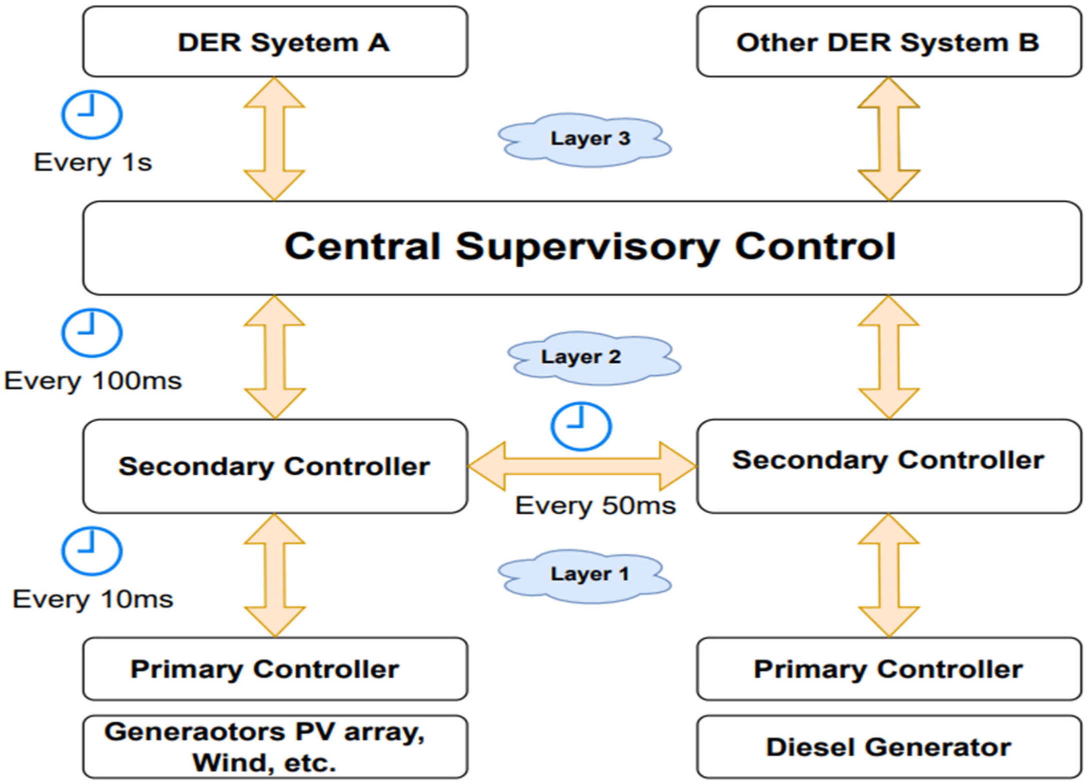

Figure 1. Distributed energy resources communication framework.

Each energy production unit, including a wind turbine, a solar panel array, and a diesel generator, has its remote control the generator unit under its primary controller unit. Primary power generation can be started, stopped, and controlled by a controller. The serial-to-analog interface is mostly used by the primary controller to communicate with the secondary controller. Secondary control has a very important role to play. It sends status updates vertically to central supervisory control systems and horizontally to other secondary controllers. Secondary control keeps track of the condition of the generating units and manages its physical features depending on important data such as the voltage, frequency, and the condition of its circuitry, among other things. The connection between the primary and secondary controllers has the maximum message frequency. Many messages must be sent out frequently for collecting and addressing the transient behavior of generators. Primary controller to secondary controller message update cycles are 10 ms, secondary controller to secondary controller message update cycles are 50 ms, secondary controller to central supervisory controller message update cycles are 100 ms, and distributed energy resource systems to distributed energy resource system message update cycles are more than one second [8].

In this paper, a comprehensive review of renewable energy communication is carried out. An attempt is made to analyze recent research articles published within the last 7 years on this subject The major objective is to identify the current status of articles published in a reputable journal, to highlight the gaps in these articles, and to proffer solutions/suggestions that enhance effective communication in the future electrical power systems grid.

Many authors have conducted reviews on the smart grid or smart systems communication. Smart systems as used in this paper is a more general term that refers to smart grids, smart homes, and vehicle-to-grid. However, smart grid/systems technology, being an emerging technology, attracts a lot of research interest and hence has prompted the need for a holistic, up-to-date review of its communication aspects. The purpose of this research is to provide an all-encompassing, up-to-date, and succinct but comprehensive review of smart systems communication to ascertain the research challenges and future research direction. A comparison of our review with some recent review papers on the same subject, as shown in Table 1, clearly shows the contribution of this work as:

- Presenting an up-to-date, all-encompassing, and very comprehensive review of smart systems communication.
- Identifying research gaps presented under recommendations and future work.

Table 1. Comparison of some recent review papers with our review.

Authors	Year of Publication	Summary of the Content of the Review Work	The Highlight of the Work
Abrahamsen et al. [9]	2021	Overview of smart grid, smart grid applications, smart grid communication, QoS requirements, interoperability, communication network structure, communication technologies, challenges of smart grid communication, and security.	Focused on the different communication layers and communication challenges.
Deepika et al. [10]	2021	IoT, cloud computing, fog computing, edge computing, comparative analysis, IoT simulators, and test beds.	Mainly discussed IoT and related technologies.
Razu et al. [11]	2020	Communication systems and smart home, networking, smart grid, cloud computing, command methods, wired and wireless technologies, comparative analysis of technologies for the smart home.	Analyzed various forms of wired and wireless technology for smart homes and recommended a combination of both to achieve better results.
Maedeh et al. [12]	2019	Smart grid (SG)-layered architectural models, SG communication infrastructure and applications, communication standards, and emerging ICTs in SG.	The main focus is communication architectures, technologies, and their requirements for the smooth operation of the smart grid.
Anita et al. [13]	2019	Telecommunication, wireless sensor networks in SG, SCADA in SG, Block chain in SG.	SG communication technologies, data protection, and security.
Mahmood et al. [14]	2014	Wireless communication options for home area networks (HANs), wireless communication options for neighborhood area networks (NANs), smart grid applications, challenges, and issues.	Reviewed different types of wireless communication methods, their application to SG, challenges, and issues.
Ramezy et al. [15]	2018	Smart grid communication architecture overview, communication technologies available for smart grids.	A brief overview of communication architectures and technologies.
Our review		Communication standards/models, communication challenges and solutions of distributed generation resources, measurement and metering in smart systems, Inverter modulation, control, and synchronization in smart grid, technologies in smart systems protection/cyber–physical systems security, review of existing smart grids, green and smart home, building trends, smart renewable energy management system, energy storage sources for optimal performance of the smart grid, harvesting energy sources for active smart grid systems, virtual power plants for smart grid operations.	A broad discussion of smart systems communication, their standards and models, and smart meters. Algorithmic communication methods for modulation and control of grid-tied inverters. Security systems, energy storage as well as virtual power plants.

The remainder of this review paper is structured as follows. Sections 2 and 3 give the general concept of a virtual power plant in smart grid operations and, most importantly, how it affects renewable energy communication. Section 4 presents a general overview of the communication standards/models that are presently popular and describes the communication challenges and possible solutions when considering distributed generation resources. Section 5 addresses the concept of measurements and metering in a smart grid, analyzing what has been performed in the recent past and what is obtainable and needed to achieve future intelligent power systems. Section 6 analyzes the technologies that are needed to enhance smart electric power systems protection/cyber–physical system security, and Section 7 considers the review of the existing grids/green and smart home/building trends as well as a smart renewable energy management system. Furthermore, Section 8 addresses the energy storage sources needed for the optimal performance of the smart grid and critically investigates the energy-harvesting sources for active smart grid system efficient operations. In Section 9, the concept of inverter modulation, control, and synchronization in smart grids is critically analyzed and narrowed down on how to achieve effective communication through real-time information exchange, control, and automation. Finally, Section 10 gives conclusions, recommendations, and the future research direction in this area.

2. The Concept of Virtual Power Plants in Renewable Energy Communication

New technologies and policies are needed to address both developing technical and economic difficulties as a result of the rapid upward penetration of DER and the continuing trend toward a more competitive electricity market. The concept of a virtual power plant (VPP) has emerged and is employed by many scientists to manage remote generation and increase its visibility inside electricity markets. Creating a "single virtual generating unit" that can function as a conventional one and can be seen or managed on an individual basis consists of integrating multiple tiny sized distributed generating units [16]. To function as a single power plant, a group of scattered generating units, controllable loads, and energy storage systems are combined to form a virtual power plant. Both fossil fuels and green energy sources are employed as generators. An energy management system, the brains of a VPP, controls the power flows coming from the generators, controllable loads, and storage. As a result of the communication being two-way, the VPP can transmit signals to control the objects as well as receive information about each unit's present status.

The ideal VPP consists of three main parts: generation technology, energy storage technology, and information communication technology. The distributed generation technology can be classified into a domestic distributed generator, which is a small generating unit that serves individual consumers for residential, commercial, and industrial parts. Secondly, a publicly owned distributed generator does not belong to an individual consumer, and its main goal is to inject power production into the grid. Both can incorporate energy storage technology or operate without it. A very important requirement of VPPs is communication technologies and infrastructure, due to the inevitable two-way communication in its operations [17]. The VPP can be set up as a stand-alone or cloud-based installation as an information and communication technology (ICT) infrastructure to cut costs and assure security. Utilities, aggregators, retailers, and TSOs that own ICT infrastructure for daily operations typically dedicate their resources to VPP installations. However, smaller aggregators, merchants, and utilities with fewer ICT resources might benefit more from the introduction of cloud-based VPP [18].

In the downstream direction, the VPP communicates with a variety of geographically dispersed units, such as electric vehicles, flexible loads, distributed generation, battery energy storage systems, and renewable energy resources, allowing them to quickly respond and supply the necessary capacity for ancillary services. To integrate the VPP into the operation of the power system network, the VPP communicates independently with electricity retailers, aggregators, TSOs, DSOs, and the energy market in the upstream direction [19]. Figure 2 shows the VPPs concept. Both commercial (CVPP) and technical (TVPP) are possible VPPs. By placing bids on ancillary service marketplaces, CVPPs make it easier to trade DERs as a flexible resource in different energy markets, as opposed to TVPPs, which combine DERs from the same region for technical reasons and work to alleviate local grid constraints [20].

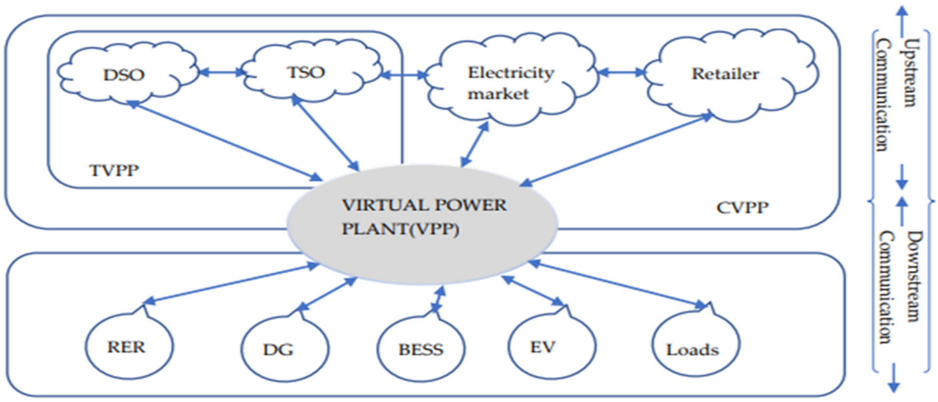

Figure 2. Concept of VPPs communication [20].

In conclusion, TCP is employed as a dependable transport protocol in the IP and Ethernet-based VPP communication system. Despite the stochastic nature of both IP and Ethernet, implementing a virtual private network often satisfies the quality of service and security requirements [21]. The architecture of the VPPs communication systems is depicted in Figure 3.

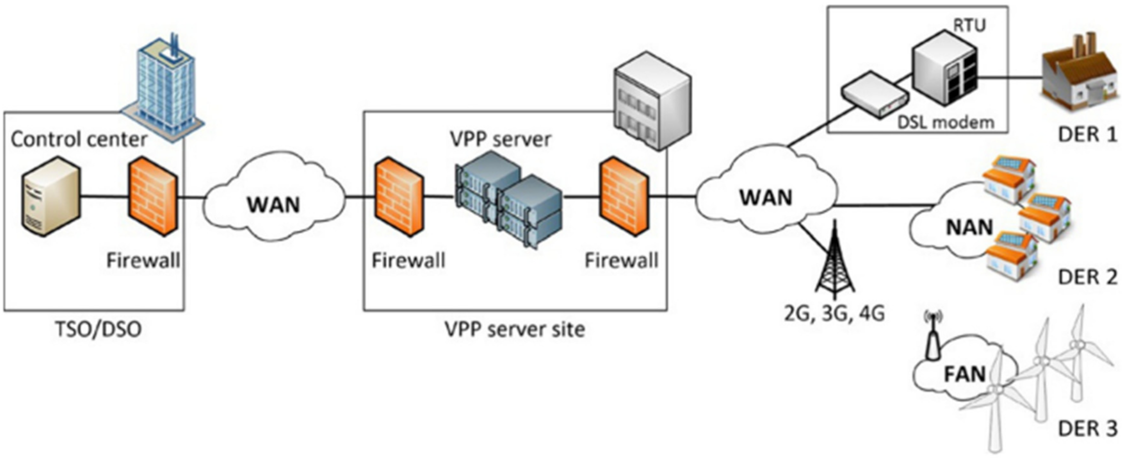

Figure 3. The architecture of VPPs communication system [21].

3. Virtual Power Plants for Smart Grid Operations

Inadequate coordination of the many communication networks used in various smart systems is a challenge for utilities. The integration of the power system, energy resources, and information technology is the cause of this lack of interoperability [22]. The network's adoption of improved communication protocols and the penetration of distributed generators (DGs) make a grid smart. If DER and DG penetration is high and they are not adequately integrated, the main grid will have power losses and low power trading [23]. A decentralized method of energy dispatch is made possible by the proper coordination and aggregation control of DG units, which also enhances the distribution network and increases energy generation. This idea envisions "virtual power plants" (VPP). VPP is a crucial component of the smart grid; this is made feasible by the network parts' ability to coordinate themselves and the grid architecture's ability to be controlled to its fullest potential. Due to the utilization of certain smart grid DGs in VPP principles, there is less overlap between the two. For example, the desire for strong active power management on distribution networks for the best performance of the smart grid is immediately applied to VPP, delivering comparable solutions to the network's issues. Because of this, different researchers have been able to define VPP from their perspectives. The authors in [24,25] state that VPP is a system that assembles numerous low- and medium-power DG units and energy storage devices by managing flexible loads on the grid to engage in power trading on the energy market or to offer backup energy services. The mechanism used to control DERs, flexible loads, energy storage devices, and the medium used for information exchange between the grid and energy users can also be used to define VPP [26]. The term VPP is used by the authors of [26] to describe a single power plant with an upgraded energy management system (EMS) that manages the operation of DERs, flexible loads, and energy storage devices. In contrast, the authors of [27] view VPP as an energy market with trading platforms for DERs that are bound by distance, capacity, size, and resource kinds.

After reviewing the numerous definitions, it is clear that the primary goal of VPP is to maximize the advantages of a smart grid by assuring correct information interchange between the supply and demand of energy [28]. The management approach suggested in [29] expands virtual power plants' ability to provide first-rate energy services, enhance productivity, and enhance demand-side management. By permitting market participation, work has been performed on managing, planning, and controlling VPP. From low-voltage (LV) loads through medium-voltage (MV) substations to high-voltage (HV) virtual power plants, Cipcigan et al. designed an architectural concept for VPP with three aggregated echelons [30]. In contrast to the suggested architecture, multiple DG penetrations restrict voltage rise, thermal limitations at LV/MV substations, and transformer ratings [31]. The communication standards/models, communication challenges, and solutions of distributed generation resources are thoroughly described in the proceeding subsection.

4. Communication Standards/Models, Communication Challenges, and Solutions of Distributed Generation Resources

The future power grid will also depend heavily on developments in information and communication technologies, such as wireless sensor networks and wireless communications. These technologies are now developing to the point where they can be modified to operate electricity grids. The next-generation power grid will be constructed on top of a new, all-encompassing IT infrastructure that offers superior coordination, monitoring, and control capabilities than those currently in use. All equipment and entities engaged in the generation, distribution and consumption of electricity will require quick bidirectional communications, which will be provided by this IT infrastructure. As a result, even if the needs of the smart grid will differ depending on the application, communications in this infrastructure will be commonplace, flexible, fault-tolerant, and reliable [32].

4.1. Communication Standards/Models

This section categorizes the smart grid communication network standards that have been developed and should always be taken into consideration when developing and implementing new power system infrastructures. Figure 4 shows a conceptual illustration of the smart energy grid's design, which is built on distinct operating sectors. This conceptual strategy offers the architectural context needed to describe, examine, and design new standards while also documenting and analyzing the compatibility of existing ones. Within this architecture, the various domains communicate with one another in their ways using various communication architectures, including wireless, power line infrastructure or wired networks, the accompanying gateways, and the relevant standards [5,15]. A succinct explanation of the connecting modes is depicted in Figure 4.

A smart grid network's major components all communicate with one another via standards that are provided by standardization groups because the telecommunications industry is continually growing [33]. Detailed presentations of the various smart grid applications and the unique characteristics of the user communications technologies are provided.

The primary necessity for smart transmission systems is the full integration of cutting-edge equipment from flexible alternating current transmission systems (FACTS) and high-voltage direct current (HVDC) transmission systems for the optimization of load flow and stability of the entire network. Serial connections, as described by the IEC 60870-5-101 and 104 and DNP3 Secure, are commonly used by the sub-stations that support the monitoring and coordination processes of FACTS and HVDC technologies, and they typically operate at low bit rates of 64 kbps [34,35]. Because no interface is built to take use of larger bandwidth, transmission rates are kept to extremely low levels even when Ethernet technology is employed. This prevents them from sending big volumes of data. Additionally, the IEC 60870-5 standard is incompatible with the complete range of IP network technology requirements, which causes operational issues. Since the data interchange in these standards is solely based on TCP/IP and provides interfaces for HVDC and FACTS, this sort of communication is only conceivable and covered by IEC 61850, Ed. 1.0-2.009-12 Network 2021, 1 135 42/136 and newer [36,37].

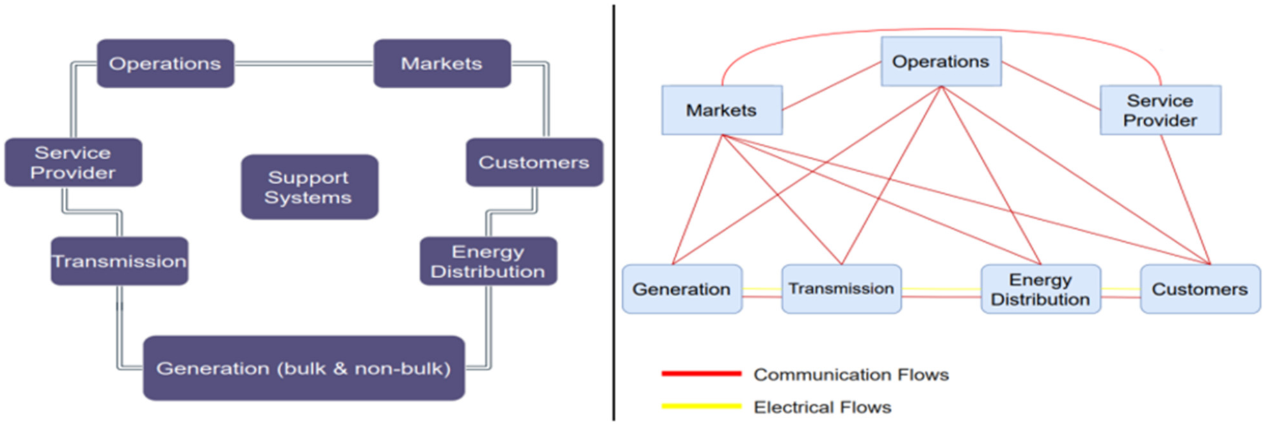

Figure 4. Smart grid domains and communication paths between smart energy grid domains.

To implement blackout prevention management, customized, bandwidth-intensive measurement systems must be incorporated. Examples include remote monitoring technologies, system integrity protection schemes, and power quality control systems, which reduce the likelihood of a prolonged power outage in an emergency [38]. Deploying a communications protocol capable of supporting broadband communications services as well as a vast network of sensors is a fundamental necessity for fulfilling the aforementioned specifications. The only globally acknowledged standard that supports broadband TCP/IP connections for the exchange of high-, medium-, and low-voltage metering data is IEC 61850 [37]. The integration of synchro phasors is also permitted by IEC 61850, which complies with IEEE C37.118 [38].

Advanced distribution management is invaluable in achieving the future smart power grid. The energy distribution system, which is assisted by information technology on topics such as security and optimization, is the most advanced component of a smart grid. The communication requirements for these distribution networks are very complex due to the networks' extensive service area and the variety of telecommunications equipment used [33]. IEC 61968 compliance is required for several broadband services that are now offered, and this standard also offers compatibility for network optimization, upkeep, and growth. The advanced metering infrastructure (AMI), which is part of the smart grid infrastructure, plays the unique role of connecting the distribution network with the systems of distributed energy resources, smart metering, industrial automation, building automation, and e-mobility. It enables interactive contact among service providers, customers, utilities, and suppliers, and includes systems for data gathering and analysis as well as energy audits [39,40]. The AMI integration can employ any suitable wired or wireless communication technology. The primary AMI standards are AEIC Guidelines v. 3.0, IEC 61968 to 9, and IEC/TR 62051, along with a plethora of parallel and occasionally incompatible standards with numerous functional variations created in various nations/geographic regions without the explicit definition of distinguishable subgroups of prevalent semantics. Due to this, it is challenging to establish a set of requirements that apply to all standards to facilitate the flow of classified information [35].

The Home and Building Electronic Systems (HBES) and Building Automation and Control Systems (BACS), according to ISO 16484-2 and ISO 16484-3 standards, refer to the infrastructure necessary for the monitoring, automatic control, manual intervention, and management of optimization services, including indoor installations and other equipment [41]. Alternative renewable energy sources, such as solar panels and wind turbines, as well as energy storage technologies, such as electric vehicles, can be handled by or integrated into HBES/BACS systems [42]. The implementation of HBES/BACS incorporates all TCP/IP-based wired and wireless communication innovations through the development of the following standards: IEEE P1701 to IEEE P1705, ISO/IEC 15045, ISO/IEC 15067-3, China: GB/Z 20965, EN 50491 series, USA: ANSI/ASHRAE 135, EN 13321 series, ISO 16484 series, ISO/IEC 14543-3, EN 13757 series, EN 50090 series, EN 50428 [15].

4.2. Communication Challenges, and Solutions of Distributed Generation Resources

Distributed energy resources (DER), which are made up of energy sources and loads, can be integrated with the help of the smart grid due to its adaptable and robust structure. The term "microgrid" refers to the small grid created when DERs, loads, and control units are combined. The two aspects of DER integration into the microgrid system are electrical and communication. The IEEE 1547 standard addresses the unique issues associated with electrical integration. However, there are still issues with the multi-vendor DERs system's communication and information integration. The only standard that provides an information model for DERs at this time is IEC 61850-7-420; however, DER manufacturers are not entirely on board with it. However, substation protocols such as GOSSE, MMS, and DNP3 that are mapped to IEC 61850 may not be sufficient to meet DERs-to-DERs communication requirements [10].

Distribution network operators (DNO) will face new challenges as a result of the addition of DER to the electrical grid. Small renewable sources will increase grid dependability and lower operating costs by being integrated into power networks, providing customers with a more affordable choice for their energy needs. They will also assist in supplying remote consumers. However, operating this new system effectively would also need a new control system [32]. In general, the distribution network must be adaptable enough to identify alternate routes to feed the specified consumers or to reroute the flow of surplus power toward other grid segments [43]. The fundamental network topology will need to be changed in such a situation, and DNOs' control systems would need to move from a passive control model to a more active control model so that the distribution network can be changed and reconfigured flexibly in reaction to modifications in the power flow [44]. The power grid must be continuously monitored and managed in real time for active control to function. As a result, many more sensors must be installed than are at present to effectively monitor the state of the electrical network. The complete distribution network will need to be used for these measurements. Therefore, the implementation of an active distributed control system design depends on the availability of high-efficiency and widespread communications infrastructure.

Communication in an independent active control is shown in Figure 5. However, it is crucial to first comprehend these mechanisms' communication needs before putting them into practice. Active control requires two types of connectivity, one between intelligent controllers and the other between intelligent controllers and field devices. To provide cooperative and distributed control over the electricity network, smart controllers must be attached. With this connectivity, the controllers will be able to communicate with one another to coordinate any control actions that will be carried out through the power network. Similar to this, controllers require the ability to deliver control commands to actuators in the field, as well as input from sensors in the power network, to carry out control operations. These specifications demonstrate that interconnections will be required to carry two distinct forms of data transmission: the first will be used to convey messages for coordination among controllers, and the other will be used to relay monitoring reports from field devices.

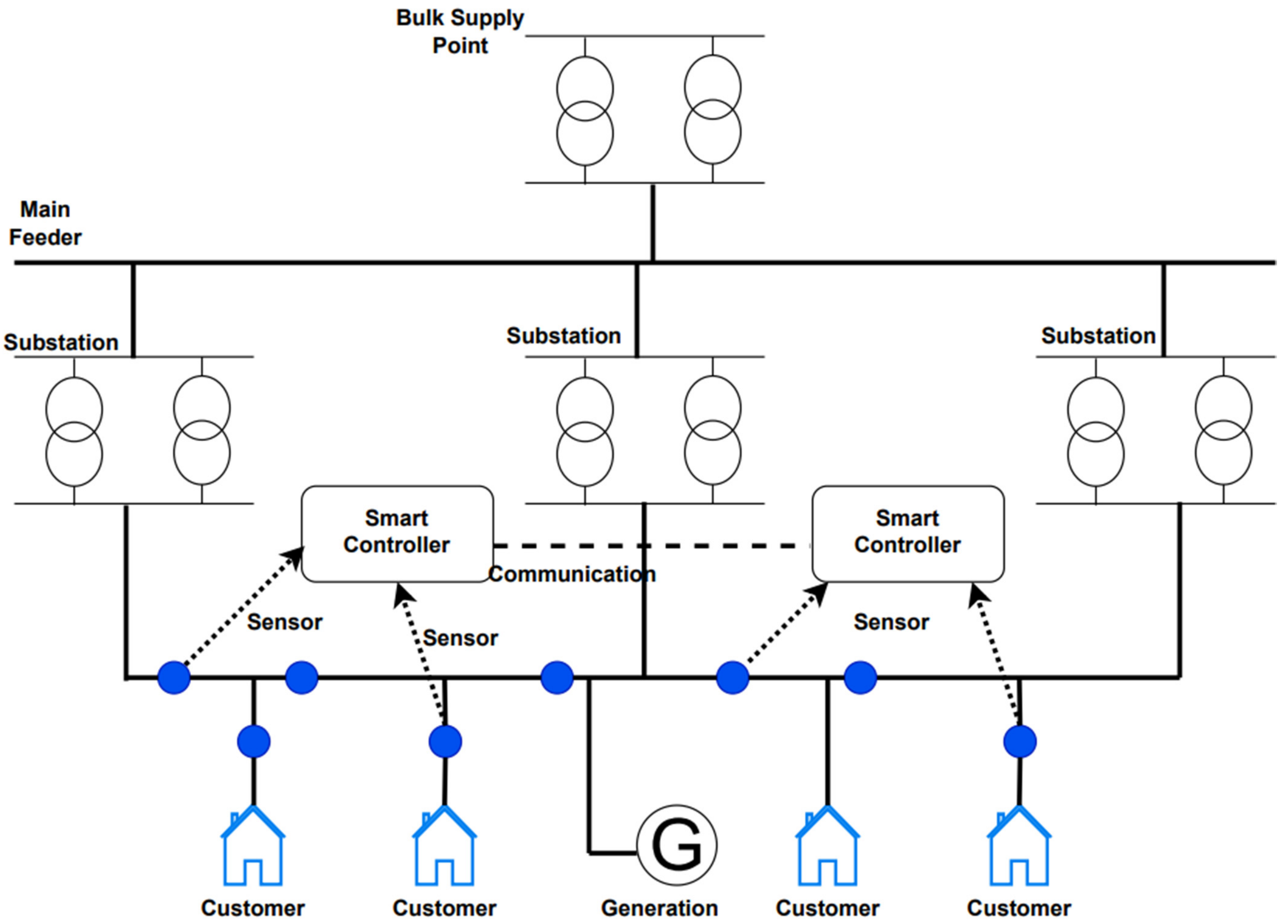

Figure 5. Communication in an independent active control.

According to the authors in [39], adding active control systems to manage small distributed generators increases the grid's communication traffic overheads, which, if not managed properly, may cause congestion and message loss, which in turn could jeopardize the effectiveness of the grid control operations. In conclusion, as a result, it is urgently necessary to upgrade the transmission capacity of the current communication infrastructure to accommodate the additional control traffic. Furthermore, additional communication channels will need to be established in linking intelligent controllers and facilitating the coordination of traffic. Advancement of the communications networks, however, will necessarily entail a complete analysis of existing communication technologies in terms of cost, performance, and ease of deployment.

5. Measurements and Metering in Smart Systems

Smart meters play a multifaceted role with cognitive capabilities in the smart grid to suit consumer expectations and each purpose. The use of a smart meter allows for the accurate measurement and real-time communication of electricity usage as well as the facilitation of remote real-time monitoring and control of power consumption, (e.g., AMI). The phasor measurement unit (PMU), which is a sophisticated measuring device that incorporates commonly used communication technology such as GPS has been developed. Based on a shared reference time, it may synchronize the system characteristics from various points throughout the grid. Voltage restrictions, low-frequency oscillation, temperature restrictions, frequency deviation, etc., are a few examples of these characteristics. The use of such devices by system operators allows them to immediately and dynamically initiate protective or regulating measures by collecting the sampled measurement data of higher frequencies to determine the state of the system [45]. To monitor, regulate, and operate the system effectively and dependably, system parameters must be measured, utilizing sensors. Measurement, monitoring, and control systems frequently employ sensor networks with communication protocols. Electrical, electromechanical, communication, oil and gas, and other systems fall within this category [46]. To monitor issues such as conductor failure, and the poor nature of the power grids, it was suggested in [47] to integrate sensor networks into the power grids. The monitoring and real-time control of the current grid can be improved using the Internet of Things (IoT). Consumers are also given access to real-time pricing and analyzed usage information, which is technical data that must be transmitted to the grid, which house utility providers. Future intelligent grids are projected to be increasingly closely connected with the control, and cyberinfrastructure for sensing, scheduling, billing, dispatch, and cyberattack detection via smart meters and online power demand orders [48]. The most crucial part of the AMI that connects each home's energy management system to the grid is a smart meter. Smart meters for power strips can be used to directly monitor and manage electricity usage at specific power outlet ports. The AMI home network, local area networks (LAN) or wide area network (WAN), data measurement and management systems, and measurement data management system (MDS) billing are all components of an advanced smart metering system that is based on AMI. Customers can access energy services through the home network, which includes two-way communication with the meter inside and outside the home. Computers and local networks are connected through WANs. Depending on the specific communication technology used, the WAN in the AMI transmits data between the measurement system and the MDS, which may contain both LAN and WAN networks or just WAN [49].

The differences between the future intelligent measuring system and the traditional measuring system are detailed in [50] where the authors concluded that the amount of data created by the intelligent meters are significantly greater than that of the traditional electricity meters since they have a variety of advanced application apps and a multi-mode grouping design. The traditional centralized reading operations, however, use a fixed setup, which is unable to meet this demand for dynamic expansion. In summary, the traditional measuring system is capable of completely satisfying the needs of electricity meter data collecting. In contrast, all types of data generated by electricity meters have recently experienced fundamental changes in terms of data volume, data type, and data characteristics, necessitating an urgent need for an intelligent measurement system to adapt. Smart electricity meters have operating systems and rich application functions. The comparison between the traditional meter and intelligent meter architecture is depicted in Figure 6.

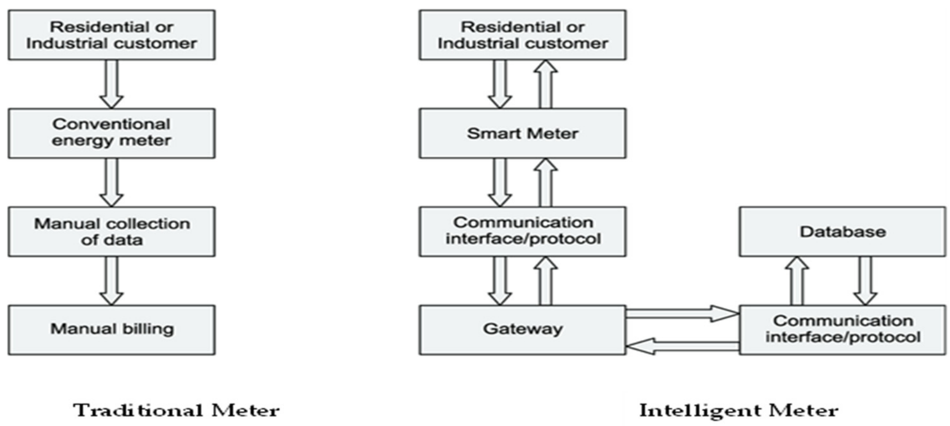

Figure 6. Traditional meter vs. intelligent meter architecture comparison.

6. Technologies in Smart Systems Protection/Cyber–Physical Systems Security

The main goals of the security architecture for smart systems are to ensure the continuous availability of service, ensure the integrity of communicated information, and keep user data confidential [51]. To achieve these, smart systems need to be adequately protected from attackers/hackers who may attempt to hold the system to ransom or exploit its vulnerability for personal benefit. Many such attacks on smart systems have been recorded in the recent past. Examples are false data injection to sensors in the smart grid to interrupt data acquisition, denial of service aimed at disabling communication with the brakes in a smart car, and replay attacks on the network's control systems to delay or corrupt control commands, etc., as reported in [52]. The attack on a cyber–physical system can occur in different layers of the system viz. the physical layer, network layer, and control layer. In the physical layers, sensors/actuators can be hacked or the distribution network for denial of service. Network layer attack usually involves manipulation of the communication signals such as in man-in-middle, information leakage, and denial of service [42]. The control layer is very critical because a small change in the control signal can cause a devastating effect on the system. The control can be manipulated to carry out any other form of attack.

Several different technologies have been developed for smart system protection, which include: encryption, authentication, malware protection, network security, remote-access virtual private network (VPN), risk/maturity assessment, site-to-site VPN, intrusion prevention system (IPS), and intrusion detection systems (IDS) [51]. Data encryption is used to ensure that when a system is connected to the Internet, the stream of data will not be readable if intercepted by a hacker. The 256-bit advanced encryption standard (AES) is being used in most technologies today. Authentication technology is used to restrict/control access to the network to ensure that only registered users can access the system. It is also used to control what data each category of user can access. Malware protection is used to secure embedded systems connected to the smart grid. Network security uses VPN to provide a secure path for communication through data encryption, remote access VPN uses a public network (e.g., the Internet) to provide access to an organization's private network after authentication, while site-to-site VPN is used by large organizations to connect different branches in their network. Detection/prevention of threats is handled by the IPS and IDS technology. Machine learning (ML) is being increasingly used for cyber–physical system protection such as online anomaly detection, and ML-based online monitoring for controllers, due to its ability to handle complex computations efficiently. However, it has some security vulnerabilities such as data poisoning and hardware attacks as its major drawbacks [52].

In summary, this section has explored the different technologies used in smart system protection. As we continue in our journey to a smarter world through the development of smart homes, smart grid, etc., security of such systems will continue to be of utmost concern to guard against unscrupulous individuals who may exploit any observed system vulnerability of the system to launch an attack for personal gains. Continued research on improving the smart systems security technologies and periodic update of security architecture for smart systems is highly encouraged to give no room for hackers to discover any inherent vulnerabilities. Several security technologies have been presented, and each technology has its own drawback. To ensure adequate security for the smart system, a combination of these methods is required to be used such that the drawback of one technology is compensated by another. ML-based security systems, as an example, can be further strengthened by such technologies as data encryption, authentication, risk assessment, or IPS/IDS.

7. Reviewing the Existing Grids/Green and Smart Home/Building Trends/Smart Renewable Energy Management System

The use of renewable energy is increasing due to the high energy demand. Energy from fossil fuels is currently expensive due to rising oil prices and, in some cases, environmental concerns. Smart grids and green energy have been identified as critical components of solutions to the problems that energy consumers face in obtaining an adequate amount of energy for their daily activities. A network that makes use of strong two-way communication, cutting-edge sensors, and decentralized computers is referred to as a "smart grid". A grid needs to be smart to increase the effectiveness, dependability, and security of grid supply and use [53]. A smart grid is essential for enhancing controllability, incorporating renewable energy into the grid, and offering a response to the rising demand for electricity. A distribution system's features have been enhanced by the usage of a smart grid, and there are numerous additional advantages [54]. A smart grid system was produced with the recent development of new renewable energy sources through the suitable use of information and communication technology (ICT) and methods of integrating energy sources [55]. The smart grid system represents a new transition away from conventional energy sources toward an energy generation that is more flexible, collaborative, and intelligent. Power generation, transmission, and distribution are now managed by a bi-directional automated system as a result of the new energy era in the energy sector [56]. This section examines the advantages and characteristics of smart grids, renewable energy management systems, and energy trends for smart homes and buildings.

7.1. Smart Grid Renewable Energy Management Systems

There have been many studies conducted on the smart grid using information and communication technology (ICT) and sensory devices that provide both residential and commercial houses, offices, and consumers with a wide range of advantages. These advantages include enhanced resistance to malicious assaults, increased energy capacity, and efficiency, lower utility costs for consumers, reduction of peak energy demand, creation of additional jobs, and integration of more renewable energy sources into the grid, self-governing control, which boosts system dependability, opening doors for fresh goods, services, and market places, allowing for distributed power generation, automated upkeep and operation, better facility usage and postponing the construction of new power plants, empowerment of self-maintenance, and decreased greenhouse gas (GHG) emissions [57–60]. The sophisticated gadgets they employ and the services they offer in exchange, which are not possible in ordinary grid systems, are characteristics of smart grids that set them apart from normal grid systems [61].

7.2. Smart Homes/Building Energy Trends

The introduction of smart houses has helped smart grid technologies to recently build a positive reputation and obtain a wider acceptance, observed globally. The recent global search for smart technology was sparked by the changes seen in smart market products and energy management systems [62]. The usage of smart grids in our residences, workplaces, or other structures has several advantages. The advantages have long been demonstrated to help residential, commercial, and industrial energy customers with their energy problems. The advantages of smart homes/buildings have been highlighted in many research studies, and they include lower energy costs, energy safety, flexibility in energy import/export systems, and personal thermal comfort [63]. Table 2 lists a few definitions of "smart homes" that can be found in articles dating back to 2008.

Table 2. Definition of smart homes/buildings by some researchers.

Author(s)	Year of Publication	Definition
Marikyan et al. [64]	2019	This home uses cutting-edge technology to give energy customers top-notch services.
Gram-Hanssen and Darby [65]	2018	It entails the connecting of sensors, appliances, controllers, and other equipment for remote monitoring and control to offer inhabitants consistent energy services.
Shin et al. [66]	2018	Smart homes are referred to as intelligent settings that gather and apply information from their occupants and their surroundings to achieve their objectives.
Strengers and Nicholls [67]	2017	Smart homes are multipurpose systems that include home ICTs, automated gadgets, and the Internet of Things (IoT).
Hargreaves and Wilson [68]	2017	A house that enhances its ability to manage various domestic systems by using data gathered from the domestic environment to provide information to the residents.
Saul-Rinaldi et al. [69]	2014	Smart homes are a two-way communication channel that interfaces between homes and their occupants.
De Silva et al. [70]	2012	Using ambient intelligence and automatic control techniques, this homelike environment can respond to the wants and desires of the residents.
Chan et al. [71]	2008	A smart home will offer the vulnerable and aging populations of the world care and protection at a reasonable cost.

There is no common definition for smart houses or buildings, notwithstanding the definitions offered by several researchers [72]. The use of smart technologies is being expanded beyond just houses and buildings. After reviewing works conducted on smart building/home technologies and applications, the current technologies are built on data and communication networks that connect them to energy management systems and energy users [73]. To provide a higher level of living and an appropriate working environment for the general public, smart homes and buildings offer a variety of services that are grouped into several technological ideas. As depicted in Figure 7, the authors in [73] divided them into three categories: using a holistic approach, energy management, safety, and lifestyle support.

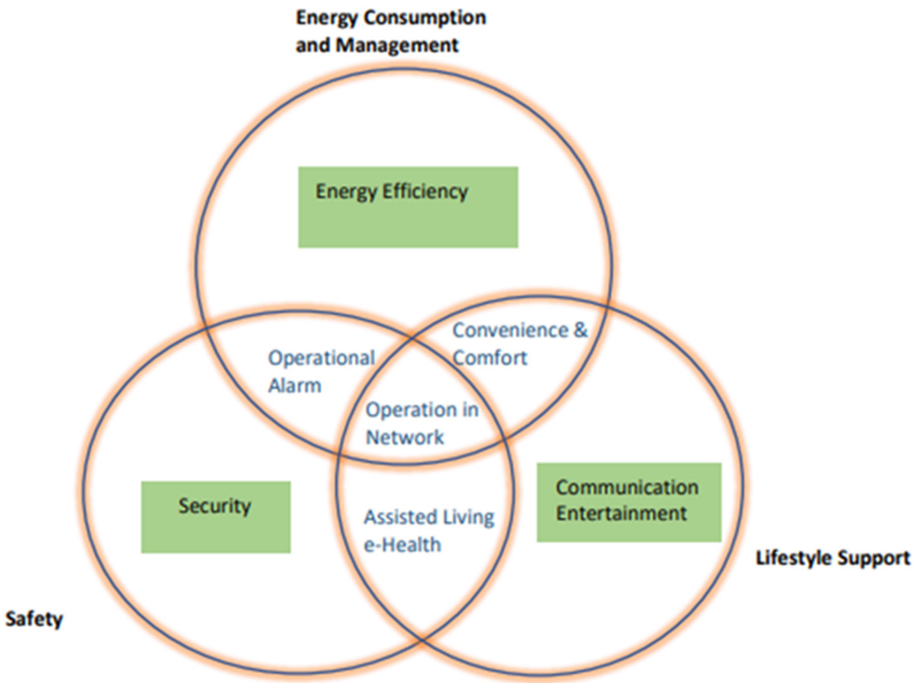

Figure 7. Smart homes/building services.

According to the desired services, the various types of smart buildings or residences are categorized in Figure 7. The primary service that underpins the advancement of the smart grid is energy consumption and management, among these categories.

Lutolf [71] researched the main contributions, uses, and advantages for energy users of smart home/building systems. Common application areas and client advantages are their main focuses. However, the authors of [72] examined the background and reasons for social scientists to participate in smart homes. The future elements of smart houses and buildings as well as domestic technologies for smart homes are the main topics of discussion. By examining the cutting-edge infrastructure and household appliances, an overview of the architecture and functionality of SHEMS modules was offered [73]. In studies of a similar kind, intrusive load monitoring (ILM) and non-intrusive load monitoring (NILM) were presented as state-of-the-art for home appliances and energy management [74]. The concept of load monitoring, energy monitoring instruments, and strategies for reducing energy and cost are the main topics of the study.

In conclusion, despite the substantial amount of research that has been performed in this field, this section focuses on reviewing the advantages of smart homes and buildings, as well as the supporting technologies and applications that relate to smart houses, city energy, and their environment. Having energy management systems recently has been a significant manifestation of home appliances for houses and buildings. To integrate electrical gadgets, smart home energy management systems (SHEMSs) are crucial. They integrate energy systems into a network for communication that may be used to run voice-activated controllers and other smart home technology as well as cell phones [68,73,74].

8. Energy Storage Sources for Optimal Performance of Smart Grid

For a smart grid to operate sustainably, the energy storage system is a crucial component. It plays a crucial part in enhancing the penetration capacity of renewable energy storage (RES) into the system by supplying backup power to the power system's hardware. Due to several atmospheric restrictions, RES electricity production is rather unpredictable. Therefore, RES penetration into the smart grid may result in disruptions or dysfunctional operation and planning of the power systems [75]. Energy can be transformed into several different forms before being stored; therefore, it is important to correctly identify the type of storage that is best for a given system. Renewable energy applications can make use of a variety of renewable energy storage system (RESS) technologies. This section provides an overview of various energy storage technologies for the penetration of RESS and optimum smart grid performance.

8.1. Energy Storage Technologies

To meet the needs of consumers, energy is changed into various forms so that it can be stored for later use. Therefore, for continual availability and sustainable power delivery, electrical energy is transformed into gravitational potential energy, compressed air, electrochemical energy in batteries and flow batteries, chemical energy in fuel cells, kinetic energy in flywheels, and the electric field and magnetic field in inductors. Utilizing cutting-edge technologies such as pumped hydro storage (PHS) systems, compressed air energy storage (CAES) systems, and battery energy storage (BES) systems, the energy storage sources are properly managed or improved. Energy may be stored for a long time in big quantities using pumped hydro storage (PHS) [76,77]. Water is pumped from a lower reservoir to an upper reservoir when there is little demand for power, allowing it to run on the gravitational potential energy [61]. The twenty-four-hour time-scale applications of PHS can be separated into a lengthy energy storage period, and this might last for a few days as reported in [78]. An example of a PHS operation is the first hydro company, which was installed in 1984 with an operating power capability of 1728 MW for 5 h at high pump rates [78]. A hybrid ultra-capacitor and battery storage system was suggested in [79] as a way to offer large consumers power control services. By reducing the battery's anomalous energy usage, the proposed energy storage technology intends to increase the profitability of regulation services. However, significant energy firms from around the world are showing interest in electric vehicle (EV) technology. Moreover, plug-in electric vehicle (PEV) owners receive hourly electricity costs via a smart communication system after the energy hourly computation using an optimization framework [80]. The electrical grid must be connected to a significant number of electric vehicles. Integrating electric vehicles into the grid will benefit energy users by allowing for proper energy sharing and control, smart charging and discharging of energy storage devices, and a reduction in grid power fluctuations.

Battery Energy Storage (BES) Technology

Electrochemical energy is a form of energy that can be stored in batteries. Considering its large storage capacity, it is the most widely utilized energy storage technique. To achieve the necessary voltage and capacity, battery energy is stored in groups of numerous cells, which are connected in series, parallel, or both [81]. Recently, some researchers in [44] performed active–reactive optimal power flow (A-R OPF) on a distribution network with embedded wind generation and battery storage. It was stated that the charge and discharge cycle for a battery storage systems' (BSSs') daily operation is based on a fixed length in the battery storage solution. Secondly, with the use of extended A-R OPF known as the flexible battery management system (FBMS), the length (hours) of the charge and discharge periods of BSSs for each day are maximized. The complexity of the mixed-integer nonlinear program (MINLP) problem makes it difficult for the proposed method to solve the problem, which is a negative of this approach. Due to the inconsistent daily weather, wind farms often experience imbalances in the amount of power produced. As a result, Ahmad Ghasemi et al. [80] established an optimization methodology that makes use of PEV and battery energy storage (BES) technology to control these imbalances. In this framework, hourly electricity rates are computed and communicated to PEV owners via a sophisticated communication system.

In [82], it is suggested that the charge and discharge paths of batteries can be synthesized using "universal" functions that have zero integral throughout the selected period. The approach has demonstrated the possibility of reducing the number of variables while implicitly satisfying the integral constraint on the volume of energy exchanged with the network. The dispatching problem is transformed into a parameter identification problem using this strategy, which is a typical engineering problem [83,84]. Integration of DGs into the grid is difficult due to the fluctuation of renewable energy sources (RES). However, hybrid energy storage systems (HESS) were developed in [85], based on complementary storage technologies that permit significant RES penetration. Of all the varieties of energy storage that support the smart grid, advanced batteries offer the greatest potential. With the proposed plan, a new power management technique is introduced for a HESS made up of a flywheel and a LiFePO4 battery connected to a 2 MW wind turbine that is running in an interconnected mode. Numerous battery types are available for energy storage, but studies have indicated that lead–acid, nickel–cadmium, and lithium-ion batteries are the most popular due to their affordability and ability to handle high-power applications [86].

For effective smart grid communication, advanced battery forms are used. The lead-acid battery is the most popular kind of battery; it has stacked cells and a diluted sulfuric acid (H_2SO_4) electrolyte. In contrast to sponge lead, the positive electrode is made of lead oxide (PbO_2) (Pb); the lead dioxide (PbO2)-containing positive electrode and lead–acid batteries' lead-based negative electrode are both internal electrodes (Pb). Both flooded batteries and valve-regulated batteries are significant subtypes of lead–acid batteries. The energy market has benefited from the widespread adoption of nickel–cadmium (Ni–Cd) battery technology. The positive and negative electrodes of Ni–Cd batteries are composed of nickel and cadmium species, and the electrolyte is an aqueous alkali solution [87]. Depending on the purpose, this sort of battery comes in two different configurations: flooded for broad industrial uses and sealed for portable devices. Ni–Cd batteries have excellent technical properties, but they are not commercially employed because of their higher cost; they are 10 times more expensive than lead–acid batteries [88].

The lithium-ion battery has an estimated two billion cells produced grossly each year; this form of battery is extensively applicable or in use in small appliances such as mobile phones and portable electronic devices [89]. For high-power devices such as stationary energy storage and electric vehicles, it is primarily used in the field of materials technology. Its function is based on the electrochemical reactions of positive lithium ions (Li+) with anolytic and catholytic active materials in the shape of a plate, which serves as a cell. The Li-ion batteries are very energy dense, with specific energies ranging from 75 to 125 Wh/kg and 170–300 Wh/l, respectively. Wakihara [90] reported high daily self-discharge, which ranges between 1 and 5% as a limitation of Li-ion batteries. Therefore, they are employed only in short-term scale applications. Despite the advantages of the lithium-ion battery thus far described, it lacks sufficient capacity to function as a backup for appliances because those appliances could entirely discharge. Secondly, because of its brittleness and significance to battery technology, it is crucial to uphold acceptable operating voltage and temperature limits. A novel battery technology that has recently surpassed existing batteries is the sodium–sulfur battery (NaS). The anode and cathode of this type of battery are sodium (Na) and sulfur (S), and ceramic beta-al2o3 concurrently serves as the electrolyte and the separator. The sodium ions interact with the sulfur anions in the electrolyte, which is a medium, to generate sodium polysulphide (NaSx), a chemical. During an opposing reaction, sodium polysulfide splits into sodium and sulfur. The disadvantage of NaS is that it operates at high temperatures, which reduces battery efficiency [91].

Table 3 lists the properties of several energy storage technologies and battery types. Through energy storage, conservation, and supply, these cutting-edge energy storage solutions maintain smart grid connectivity. It improves power export to the grid when the DGs produce excess energy and power import storage from the grid during peak periods.

Table 3. Characteristics of energy storage technologies and battery.

Energy Storage Technology	Rated Power	Storage Capacity	Self-Discharge Per Day	Life Cycle(Cycles)	Efficiency (%)	Response Time	Usability
PHES	100–5000 MW	Hrs–Mons	Very small	Nil	65–87%	1–2 min	Long term
CAES	5–300 MW	Hrs–Mons	small	Nil	50–89%	1–2 min	Long term
Lead Acid Battery	0–20 MW	Mins–days	0.1–0.3%	500–1000	75–80%	seconds	Long term
Ni–Cd Battery	0–40 MW	Mins–days	0.2–0.6%	2000–2500	85–90%	Seconds	Long term
Lithium Battery (Li-ion)	0–100 kW	Mins–days	0.1–0.3%	1000–10,000+	85–90%	Seconds	Long term
Sodium Sulfur (NaS) battery	50 kW–8 MW	Sec–Hrs	20%	2500	80–90%	Seconds	Short term
Double Layer Capacitor/Super Capacitor	0–300 kW	Sec–hrs	20–40%	100,000+	90–95%	Milliseconds	Short term

8.2. Harvesting Energy Sources for Active Smart Grid Systems

RES are usually integrated into the electrical grid through energy harvesting (EH) devices. The ambient environment is used to capture extra energy from renewable energy sources such as solar, wind, acoustic, thermal, chemical, and hybrid energy. Energy harvesting, or EH, is a technique for transforming unused energy from ambient sources into electrical energy for use in household equipment. Energy harvesting for an operational smart grid has been the subject of numerous research studies. The significance of radio frequency (RF) energy harvesting in smart grids was highlighted by Fernando et al. [92,93]. The goal is to capture energy using radio electromagnetic waves at wireless sensor nodes for the smart grid. The results demonstrate that RF harvesting is superior to other techniques. A strategy to let consumers interact with the energy market directly to alter the cost or availability of electricity is put forth in [93]. The suggested method, however, only takes into account a selection of non-essential loads that will be turned off during peak hours. Because of its hyperactive technology, artificial intelligence (AI) was a topic of consideration for researchers [94–97]. They used deep learning (DL) and natural language processing (NLP) technology because their goal included using numerous layers of neural networks and was heavily dependent on random optimization (NN). The learning capacity and performance of the various layers are enhanced, especially long-short-term memory (LSTM), which has received considerable interest in the field of time-series data learning. Although the smart grid can be energized in a variety of ways, research is presently being performed to identify the best EH method.

Energy-harvesting devices such as solar energy harvesting systems keep an eye on the home's electrical supply and make sure that all of the appliances are run entirely on solar energy. [56,98]. The photovoltaic device captures the sun's energy and transforms it into electricity. Because solar harvesters cannot produce power at night, this type of EH is weather-restricted. The maximum power point tracking (MPPT) system, which continuously tracks sunlight and the related load to maximize power transfer, has drawn greater attention from researchers as a result of this limitation [99]. Similarly, radio frequency-based energy harvesting uses wideband frequency ranges and automatic frequency tuning to increase the output power for effective energy usage [100,101]. However, Yildiz et al. [102] described Peltier, Seeback, and Thomson effects as examples of thermoelectric effects that can produce electricity using the available heat sources. When two conductors constructed of various materials are exposed to varying temperatures, the thermoelectric effect allows for the production of a voltage signal. The features and difference in temperature of materials with remarkably low values within 10 to 1 mW/cm^2 are therefore the only factors that affect the high-power density of thermoelectric generations [103]. Based on a specific consensus technique suggested by Zhang et al., many EH devices are currently in use [104]. The research shows that the control algorithm can distribute the electrical and heat power of EH devices effectively without taking into account network factors. The parameters are used to control the frequency to guarantee a decrease in parameter deviation and to limit the pressure to a reasonable range in smart system communication. As a result, to achieve self-sustaining communication on the smart grid, a combination of these EH devices must be deployed to aid in the integration of the acquired RES into the grid for the energy users [105,106].

9. Inverter Modulation, Reference Frames, Controllers, and Synchronization in Smart Grids

Inverters for grid integration of renewable energy sources (RES) are usually classified as grid-forming, grid-following, and grid-supporting inverters. Grid-forming inverters are used in mini/microgrid in islanded mode and are controlled to set the voltage amplitude and frequency for the mini/microgrid. In this control mode, the inverter is seen as an AC voltage source with low output impedance. Grid-supporting inverters offer essential ancillary services, either stand-alone or interconnected and control the AC grid voltage amplitude (reactive power) and frequency (active power). A grid-following inverter is usually connected to a bigger grid network where it operates as a current source with high output impedance and is controlled to follow the grid voltage and frequency. Essentially, the synchronization is achieved using a phase-locked loop (PLL), which measures the frequency and phase at the point of common coupling, to regulate the active and reactive power. The modulation and control methods in grid-forming/following inverters are aimed at ensuring proper communication between the grid and the RES through sensors, actuators, and controllers.

Renewable electrical energy is generated from various sources such as solar photovoltaic (PV), solar thermal, wind, hydro, biomass, and geothermal [107]. Apart from solar PV, which generates electrical energy in DC form, other renewable sources usually use AC generators. For systems involving AC generators, usually, a synchroscope is used to connect to the grid. The function of the synchroscope is to ensure that the following conditions are met:

- The voltage magnitude of the generator and the grid must be equal.
- The sinusoidal phase sequence of the generator and grid must match.
- The frequency of the generator voltage must be the same as that of the grid.
- The phase angle between the generator voltage and the grid voltage must be zero.

In the case of solar PV systems, the AC generator is replaced by a DC–AC converter, otherwise called the inverter. There are various inverter topologies, but for grid-connected PV, multi-level inverters (of different topologies) are usually used. To ensure that the grid-connected inverter meets the above conditions of synchronization, various modulation schemes have been developed and tested by researchers [108]. Inverter modulation and control can be seen as a form of algorithmic communication technique that ensures a synchronized operation between the inverter and the AC grid. The purpose of this section is to present a holistic and comprehensive review of all the modulation/control algorithms of grid-connected inverters available in the literature. This section is important since inverter-dominated power systems would be the future power system, and to achieve renewable energy communication, proper modulation techniques are invaluable. Consequently, a comprehensive review of the modulation techniques for grid-tied inverters is discussed.

9.1. Modulation Methods

The efficiency of the grid-tied solar PV system is affected by the sequence and duration of the switching pulses in the multi-level inverter (MLI) [108]. Apart from controlling current and voltage, modulation techniques are aimed at reducing total harmonic distortion

(THD) as well as reducing switching losses. This is the reason many types of modulation techniques have been introduced by researchers. We can broadly classify the methods of modulation based on switching frequency as:

- Fundamental Switching Frequency Modulation Scheme (FSF-MS);
- High Switching Frequency Modulation Scheme (HSF-MS).

9.1.1. Fundamental Switching Frequency Modulation Scheme (FSF-MS)

The FSF-MS is further classified into four types: selective harmonic elimination, space vector control, switching angle calculation, and nearest level control.

Selective harmonic elimination (SHE) is a modulation method implemented by developing the Fourier series of the voltage waveform and using the switching angle to remove low-order harmonics [109,110]. Specific switching angles are pre-determined to remove certain undesired low-order harmonics [110]. It can be applied either online or offline to the inverter and is effective in improving the output voltage waveform as well as minimizing switching losses. In recent times, to improve output waveform, the SHE algorithm has been combined with other intelligent algorithms such as the artificial bee colony algorithm in [111], the particle swarm optimization algorithm presented in [112], and the genetic algorithm in [113]. It is seen in the research results that the combination of the SHE algorithm with these intelligent algorithms not only improves output waveform but also enables the inverter level to be increased, thereby reducing the total harmonic distortion.

Space vector control (SVC) also known as nearest-level control is a modulation method in which a sinusoidal reference voltage is compared with the output voltage of the inverter to choose the nearest voltage level [114]. Using the vector nearest to the reference ensures that the error is reduced significantly. This modulation technique has been found to produce a better quality of output voltage, lower ripples in output current, and reduce total harmonic distortion (THD) [114,115]. Compared to the PWM techniques, the SVC has less complexity and lower computational time [114]. In addition, there is no need for a triangular carrier signal since the duty cycle and switching states are computed directly for each phase of the multi-level inverter.

Switching angle calculation (SAC) is known for its harmonic reduction and improvement in the quality of output voltage [116,117]. The switching angle is calculated following the number of voltage levels of the inverter. For an n-level inverter, the number of switching is $(n - 1)/2$. In [118], the SAC method was applied to an eleven-level grid-tied cascaded H-bridge inverter, and the result showed a reduction in THD. One advantage of this method as noted in [118] is that once the switching angle is calculated for minimum THD, the switching pattern can be applied for any level of output voltage. The SAC method was also used for a hexagonal-shaped fifteen-level inverter in [119] where it also proved effective in the reduction of harmonics and THD.

Nearest level control (NLC) is implemented by comparing a sinusoidal reference voltage with the inverter outputs. The output that is nearest to the reference is selected and used to generate the firing signal for the switches [116]. This way, the algorithm directly computes the switching states and duty cycle for every phase of the inverter. The method is very simple to implement, as it does not require any carrier signal. A different variant of this modulation scheme such as the modified nearest level modulation in and an enhanced level-increased nearest level modulation in [120] are available in the literature. The method has consistently shown high-quality output voltage waveform as well as a reduction in THD [116,117].

9.1.2. High Switching Frequency Modulation Scheme (HSF-MS)

The HSH-MS is broadly classified into pulse width modulation (PWM) and space vector modulation (SVM). Each of these two classes has various types, which will be explored in the following paragraphs.

The PWM is perhaps the most popular modulation technique. The PWM scheme generates the inverter gating signals by continuously varying the width of the firing pulses through a comparison of the reference and carrier signals. The PWM algorithm is either carrier-based or reference-based, hence the two groups of PWM, which are carrier-based PWM (CPWM) and reference-based PWM (RPWM) [115].

The basic principle of the CPWM for the n-level inverter is that n-1 carrier signals of the same amplitude and frequency (with different forms of phase manipulation) are compared with the reference signal to generate the firing signals of the inverter. CPWM has been widely used by different authors in several variants such as phase-shifted (PS-PWM), phase disposition (PD-PWM), phase opposition disposition (POD-PWM), and alternate phase opposition disposition (APOD-PWM) [121], as well as optimized carrier peaks (OCP-PWM) [122]. Older variants include the level shift (LS-PWM) and hybrid (H-PWM), which combine the advantageous features of phase shift and level shift PWM.

In RPWM, a reference signal is constantly compared with the carrier signal, and a pulse (which turns on the inverter switch) is produced only when the reference is greater than the carrier. This method is also very popular in the literature, and different variants have been implemented with very good performance. The various types include trapezoidal PWM, which was used to achieve higher root mean square voltage in [123], sinusoidal PWM, which was used to achieve reduced switching losses in [124], staircase PWM, which eliminated higher order harmonics and gave low THD in the work of [125], the hybrid reference PWM, which combines two reference signals to achieve better results third harmonic injection PWM for maximizing DC-bus utilization without causing over modulation [126], and the discontinuous reference PWM in [115].

SVM is a method that involves the use of voltage angle obtained from the reference voltage to select the optimal switching state of the inverter from the six vector states represented as the six vertexes of a hexagon as well as the two zero vectors that help to reduce the switching frequency [127]. SVM is a digital modulation method that generates PWM based on the sector of the reference vector [128]. The SVM technique has been applied successfully in [55] to reduce harmonics, reduce voltage stress at switches and balance DC link voltage in two-level and three-level neutral point-clamped multilevel inverters. In [129], the SVM method was also applied in three-phase, three-level diode-clamped MLI for which the results showed reduced harmonics and THD.

9.2. Reference Frames

There are three main reference frames used in the control of grid-connected MLI. These include the DQ reference fame, ABC reference frame, and αβ reference frame. Each of these reference frames is further explored in the following paragraphs.

In the D -reference frame (direct-quadrature) or synchronous reference frame, DQ currents and voltages are obtained using Park's transformation. By this transformation, the control variables (either current or voltage) are converted from the sinusoidal domain to the DC domain, which can be easily controlled and filtered [130]. This reference frame has been widely used in various types of controllers in recent times. Usually, the reference signal (current or voltage) is compared with the transformed DQ components; the error generated is passed through a suitable controller whose output is fed to the PWM modulation stage to drive the inverter. Its poor compensation for lower-order harmonics was pointed out in [108], where the authors also mentioned the non-elimination of steady-state error.

The ABC reference frame is applied to a three-phase system without any transformation. Each phase of the three-phase system is compared with a reference, and the error generated goes through a controller that feeds the modulation stage. One drawback of this reference frame is that it increases system complexity when linear regulators such as proportional–integral (PI) or proportional–resonant (PR) controllers are used [115]. However, its advantages include simplicity of transfer functions, fast reference tracking, and better harmonics compensation [108].

In the αβ reference frame or stationary reference frame, αβ currents or voltages are obtained using Clark's transformation. The transformed αβ currents or voltages are two-phase sinusoidal signals [130]. The PR controller is usually used in this reference frame, as it is less complex than in DQ and has proven its effectiveness in the elimination of steady-state error. However, its drawbacks as highlighted in include poor power factor control, slow reference tracking, and complexity of hardware implementation.

9.3. Controllers

The job of the controller (in any grid-connected inverter) is to respond to the communication signals from sensors, and through the control algorithms, initiate appropriate control action to maintain grid stability even in the case of a disturbance. To meet the requirements for grid connection, several controllers have been developed and tested in the literature. These controllers are broadly grouped into five, which include: linear, intelligent, adaptive, non-linear, robust, and predictive as shown in Figure 8 [108,115].

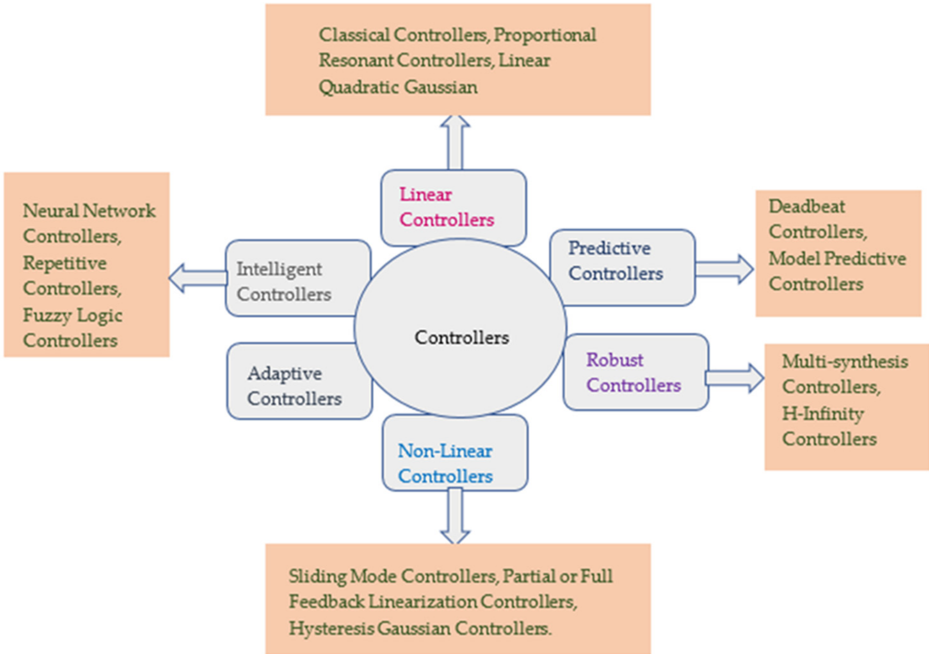

Figure 8. Classification of controllers used in grid-tied inverters.

Linear controllers are further subdivided into linear quadratic gaussian (LQG), classical, and proportional resonant (PR) controllers. Popular examples of the classical controller are the proportional plus integral (PI) [131], proportional plus integral plus derivative (PID) [132], while the less popular ones are the proportional (P) as well as the proportional plus derivative (PD) controllers. The popularity of the classical controllers is due to their simple structure as well as ease of realization in both analog and digital systems. The PR controller is very similar to the PI controller; the major difference is that PI operates in a DQ frame while PR operates in an $\alpha\beta$ frame. The PR controller has been gaining much popularity in recent times due to its disturbance rejection capability as well as its ability to eliminate phase shift and steady-state errors by integrating only the frequencies that are close to the resonant frequency [133]. The LQG controller is obtained by combining an LQ regulator with a Kalman filter. It has been found to perform very well in both time-varying and time-invariant systems. To further improve its performance, the LQG has been combined with the integral controller [134].

Intelligent controllers have gained much popularity as the need for automation continues to increase. These controllers mimic human systems such as the nervous system and replicate biological intelligence. They do not require mathematical modeling of the system and hence can be easily applied to systems that cannot be modeled mathematically. Intelligent controllers include the neural network controller (NNC), the repetitive controller

(RC), and the fuzzy logic controller (FLC). They can be used alone or in combination with other controllers [135,136].

Adaptive controllers are normally used to cater to the effect of parameter variation in a control system as the controller parameters continually change to adapt to that of the changing plant (e.g., changing load). The adaptive controller has been successfully used to ensure grid stability in many research works. A mismatch between the grid and inverter impedances can lead to harmonics, and because the grid dynamics are always changing, an adaptive controller is used to make the inverter adapt to the changing grid condition and to ensure stability as reported in [137].

Non-linear controllers include sliding mode controllers, hysteresis Gaussian controllers, and feedback linearization controllers. Most real-world systems are non-linear, making non-linear controllers a very important class of controllers. The sliding mode controller such as in [138] has gained much research interest due to its effectiveness; hence, numerous variants exist.

Robust controllers are designed to have the capability to handle system uncertainties and disturbances. They are two types: the Mu-synthesis controller and the H-infinity controller. Robust controllers can achieve system stability even in the presence of modeling errors. In the H-infinity method, the designer formulates the control as a mathematical optimization problem, and then, a controller is chosen to solve the optimization. Its main drawback is the level of mathematics involved and the complexity of the algorithm. The H-infinity controller for a grid-connected inverter is presented in [139]. The Mu-synthesis controller is an extension of the H-infinity controller, which attempts to structure the uncertainties in the system model as a measure of the robustness of the controller. Its application is seen in the work of [140] where it is used in grid-tied inverters.

The predictive controller is a digital controller that uses the present state of the plant to predict its future state. It includes the deadbeat controller and model predictive controller. Both methods have been extensively applied in grid-connected inverters such as the deadbeat method in [141] and the model predictive method in [142]. The predictive controller is famous for its ability to handle complex systems, fast dynamic response, as well as low harmonic distortion. However, it is very complex in implementation, as it requires a lot of computation.

In summary, this section has examined the various modulation and control techniques in grid-tied inverters aimed at ensuring proper communication between the grid and the RES through sensors, actuators, and controllers. We also explored the various reference frames that make these modulations and controls possible. Inverter modulation and control is one of the essential part of the future smart grid technology due to the important role it plays in ensuring better power quality, reduced harmonic content in grid voltage and current, improved grid reliability and efficiency. As we see in the material presented in this section, a lot of research effort has gone into developing better and improved modulation and control methods for the grid-tied inverter. However, a future smart grid would require more intelligent modulation techniques that can improve grid security in addition to meeting the basic requirements of power quality, less harmonic content, reliability and efficiency.

10. Conclusions, Recommendations, and Future Work

10.1. Conclusions

In this article, the comprehensive review of the importance of communication in electrical power systems has been critically examined, and an in-depth discussion on the current state of renewable energy communication modeling for smart systems was performed to know where we are, and what needs to be performed to achieve the intelligent future electrical power system, which is currently popular. The authors focused generally on all recent literature on renewable energy communication in smart systems. The concept of virtual power plants (VPP) is at the front burner in ensuring high smart penetration of renewable energy into the electrical power system grid. However, appropriate two-way communication with different entities is paramount. Therefore, it is immediately necessary to increase the current communication infrastructure's transmission capacity in order to handle the increased control traffic. It will also be necessary to develop new communication channels to link intelligent controllers and enable traffic coordination. However, to advance communications networks, a thorough evaluation of current communication technologies' costs, performances, and implementation simplicity is required.

Despite the vast amount of study that has been performed in this area, this article focuses on analyzing the benefits of smart buildings and homes as well as the ancillary technologies and applications that relate to smart homes, city energy, and their surroundings. Recent home appliances for homes and buildings have significantly manifested as energy management systems. SHEMSs, or smart home energy management systems, are essential for integrating electrical devices. They incorporate energy systems into a communication network that may be used to power cell phones, voice-activated controllers, and other smart home devices.

The various modulation and control mechanisms used in grid-tied inverters have also been extensively examined in this article in order to ensure adequate communication between the grid and the RES through sensors, actuators, and controllers. We also looked into the several reference frames that enable this modulation and control. Due to the crucial role it plays in assuring higher power quality, reduced harmonic content in grid voltage and current, enhanced grid reliability, and increased grid efficiency, inverter modulation and control is one of the critical components of the future smart grid technology. As we have discussed, significant research has gone into creating better modulation and control techniques for grid-tied inverters. Future smart grids will nonetheless need more sophisticated modulation methods that can boost grid security in addition to fulfilling the fundamental needs of good power quality, low harmonic content, dependability, and efficiency.

10.2. Recommendations and Future Work

The future power grid will continue to witness increased integration of renewable generation as the world continues to move away from fossil fuel-based power generation. The multi-level power electronic inverter, which is at the forefront of this integration, will continue to gather research momentum among smart grid investigators. The most essential part of the grid-tied multi-level inverter is its modulation, control, and synchronization with the power grid (which we describe in a broad term as a form of communication with the grid using an algorithm). The objective of the modulation technique is to improve power quality, reduce harmonic content and improve grid reliability as well as efficiency. Future research in modulation techniques should focus on the development of a grid-tied inverter control method that can provide intelligent and ancillary services that enhances grid security, power quality, and grid reliability. Modulation techniques should be combined with intelligent algorithms such as artificial intelligence, genetic algorithm, machine learning, etc., to meet the requirement of the future grid.

Since smart systems such as smart vehicles, smart buildings, smart grids, smart cities, etc., are becoming more popular and they are prone to cyber-attacks by terrorists, effort must be put into preventing attacks on cyber–physical systems and the associated losses. Future research work should in this area consider the following:

a. The use of a complex but efficient encryption algorithms and key generation/management systems with multi-step authentication should be explored in smart system protection. The security architecture should be based on a combination of different technologies and authentication using biometrics, strong/difficult password, etc., and artificial intelligence can be leveraged to enable a behavioral analysis of the network.
b. Equipping sensors, actuators, and controllers with strong user-end encryption/authentication processes to ensure data integrity and confidentiality.
c. Explore the use of deception techniques. Future IDS/IPS protocol should explore the use of a decoy set up with deliberate weakness to attract attackers for security risk analysis, which will be followed by preventive action.

In addition, future research should examine how renewable energy production uncertainty affects the economic dispatch of electricity in the VPP, the reliability of the system, and aggregator profits. Given that communication is crucial to the management and automation of VPPs, more research may be performed to determine how communication delays or disconnections affect the management of distributed prosumers in VPPs.

Finally, concerning energy harvesting, management, and storage in the smart grid operations to enhance renewable energy communication, to use machine learning to identify the latent difference in the environment, energy harvesters should analyze the signals from the electromagnetic sources. However, by utilizing tactile information, artificial intelligence (AI) should be used to acquire physical knowledge and signal sensations. To fulfill the energy demand, research should place a stronger emphasis on the technologies that may be used for energy harvesting by academic researchers and development projects.

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