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Communication Requirements in Microgrids: A Practical Survey

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ABSTRACT Progress in Microgrid (MG) research has evolved the MG concept from classical, purely MG power networks to more advanced power and communications networks. The communications infrastructure helps control and manage the unreliable power outputs that most standard power generation elements of the MG (e.g., wind turbines and photo-voltaic panels) deliver. Although communication technologies do offer certain advantages for sensing and control, they generate other complications due to packet loss and packet latency, among other transmission impairments. In this work, we discuss the impact of communications on MG performance, establishing the requirements of data exchanges and system response in the three levels of a hierarchical control approach: primary, secondary, and tertiary. With a focus on the secondary level — responsible for ensuring the restoration of electrical parameters — we identify standards, networking protocols, and communication technologies relevant for the interoperability of MGs and clusters of MGs, including both modes of operation: isolated and grid-connected. We review theoretical approaches and practical implementations that consider the effects of the communications network on the general performance of the MG. Moreover, we undertake an experimental analysis of the influence of wired and wireless communication networks on MG performance, revealing the importance of designing future smart control solutions more robust to communication degradation, especially if wireless technologies are integrated to provide scalable deployments. Aspects such as resilience, security, and interoperability are also shown to require continuing efforts in research and practical applications.

INDEX TERMS Communication network, latency, MG secondary control, microgrid, smart grid.

I. INTRODUCTION

The degree of intelligence of a Microgrid (MG) is directly influenced by the capability of the communication infrastructure to transfer real-time data between the system nodes regardless of the MG topology, complexity, and unexpected events. Therefore, choosing the appropriate communication technologies, which should concomitantly offer the required levels of reliability, security, and performance (e.g., bandwidth, latency, and packet losses), represents an important challenge. This challenge will only increase as the smart grid concept evolves with more interconnected clusters of MGs and more layers of communication technology required.

As an essential component within the future smart grid technologies [2], [3], communication systems supported by the two main media, wired (copper-based and fiber optic) and wireless, must handle a significant amount of data generated at all system levels (e.g., generation and distribution) and transmitted to nodes placed at various distances.

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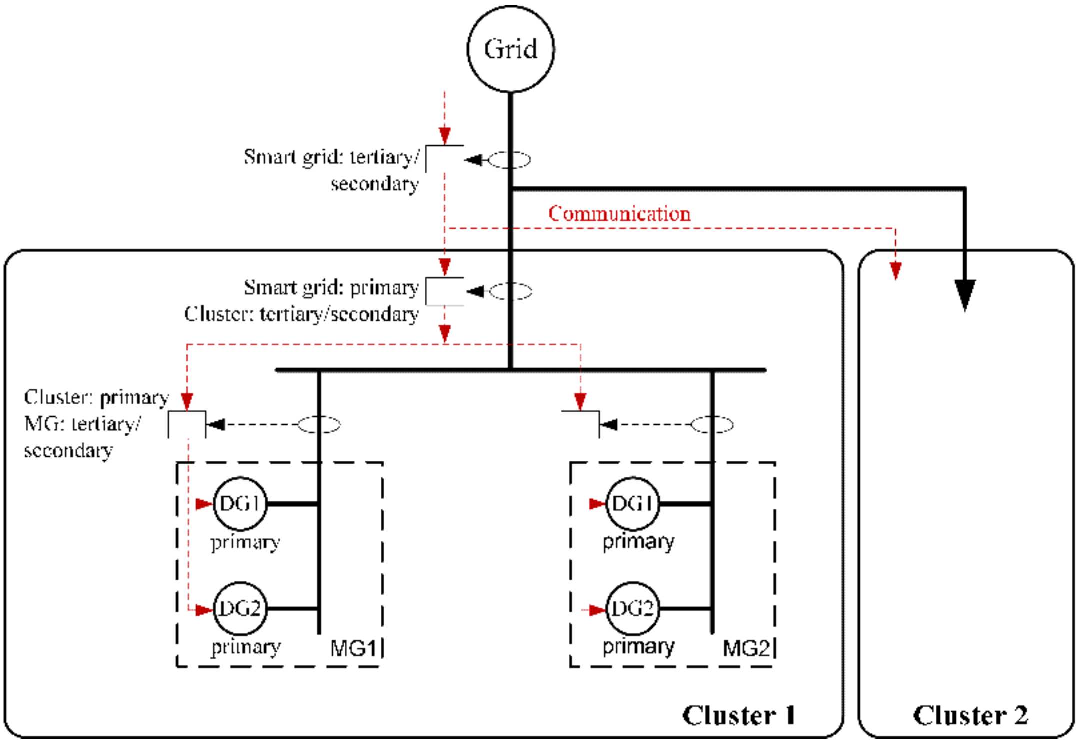

FIGURE 1. **Smart grid structure based on multi-MG clusters, according to [1]. DG: Distributed generator; SG: Smart grid.**

A number of standards are currently addressing the challenges of smart grid communication [4], [5]. However, a mandatory step for smart grid development is to establish interoperable standards for the overall system. The IEEE vision for smart grid communications [3] provides a discussion on how communications will become an integrator of various mechanisms of the future smart grid, such as demand forecasting, demand response, grid operation and diagnostics, power quality improvement, integration of renewable energy sources, and privacy and security. According to [1], in the most accepted approach, the MG is considered a building block for the future smart grid. As such, the MG must provide reliable communication pathways within itself and between MG clusters, as highlighted in the representation illustrated in Fig. 1. The interconnection of MGs into clusters follows similar architectures to those used to integrate the generators inside each MG; an analysis of possible multi-MG architectures is provided in [6].

The data exchange in an MG usually takes place at different levels, which also define the required performance of the communication infrastructure. One of the most effective ways to organize MG control consists of a three-level — primary, secondary, and tertiary — hierarchical structure [7]–[10], which was inspired by conventional power systems [1]. Whereas the performance of the first two levels (i.e., primary and secondary) affects the system's stability and power quality, involving fast control mechanisms such as droop control [11], virtual synchronous generator [12], and real-time control for voltage and frequency restoration processes, the tertiary level provides support for optimizing the MG power flow or the power transfer to/from the utility grid (when the MG operates in grid-connected mode).

The parameters of the primary (e.g., droop gains, virtual inertia, and damping coefficients) and secondary (e.g. restoration controller gains) levels define the dynamics of voltage and frequency and directly affect MG stability. Since the voltage and frequency control are characterized by different time constants (at least one order of magnitude), they can be decoupled and analyzed individually. For example, voltage in the various MG nodes can have different steady-state values within the standard ±10% interval range [13]. As the power flow changes in the system, the units providing primary voltage control act to limit the local voltage deviation in the node they are connected to by a droop-based control mechanism. The secondary control then acts to restore the voltage to the rated value by changing the reference voltages of the primary controllers. The typical performance parameters to assess the primary and secondary voltage control are the maximum deviation and restoring time.

Unlike voltage, frequency is a global parameter of the system with the same steady-state value in the entire synchronous area. Primary frequency control includes two actions: the inertial response (natural and/or virtual inertia) and the primary response to frequency deviation of the involved units. Similarly to the secondary voltage control, secondary frequency control acts to restore the system rated frequency by changing the references of the primary controllers. The adopted performance parameters of the primary and secondary frequency control are initial rate-of-change-of-frequency (RoCoF), maximum deviation, and restoring time.

The future will require more connectivity between MGs and MG clusters and the larger power distribution systems. To this end, previous works have partially addressed the interdependence among the power and communications components of an MG. Authors in [14] provide a big picture perspective on the technologies and issues that can be expected when incorporating communications infrastructure to the MG; however, most of the cited works and the conclusions are actually oriented to Smart Grids and not specifically to MGs. An analysis of the communication for multi-MG systems according to various clustering architectures is provided in [6], where the amount of communications required is shown to be an important factor affecting the cluster control type. A different approach is used in [15], in which a clear distinction between Smart Grids and MGs is made; however, the work does not analyze the importance of communication network parameters and their effects on MG performance. In a similar way, Chavan et al. [16] provide examples of implementations of communications technologies applicable to MGs, but there is no further discussion about how a technology with specific characteristics can affect the power distribution system. The work in [17] offers an overview of different types of wired technologies for MGs, but it does not include wireless alternatives.

This paper compares the existent constraints in different MG configurations relating specific communication performance metrics with the successful operation of the MG for wired and wireless technologies. We survey theoretical works, evaluations by simulations, and some practical implementations reported in the literature. Furthermore, we experimentally analyze the influence of wired and wireless communications on MG performance. Our aim is to identify the communication network requirements for stable implementations of MGs and MG clusters, as well as to analyze areas that can be improved to advance towards the MG-power-distribution system integration and MG-Smart grid integration the future requires.

The remainder of the article is organized as follows: in Section II we discuss the interdependency between the MG control hierarchy and the communication network. In Section III we describe the MG architecture requirements for a reliable, fast, secure, and real-time communication without data packet losses. In Section IV we give in-depth details regarding the impact that the communication network has on the performance and operation of MGs.

Section V includes an experimental analysis of the impact of communication on MG performance. Section VI discusses the open research challenges related to the most difficult threats that MG architecture-related communication requirements face. Finally, concluding remarks describe the technical challenges to be confronted in Section VII.

II. INTERDEPENDENCE BETWEEN THE MG CONTROL HIERARCHY AND THE COMMUNICATIONS NETWORK

Fig. 2 illustrates the MG's typical organization using a hierarchical structure formed by three levels [8]–[10]: primary, secondary, and tertiary. In the following, we describe the details of each level's function and identify the communication system's purpose for each level's internal operation. We also discuss the role of the communications network over the synchronization across the hierarchy.

A. PRIMARY LEVEL

On the lowest level, the system deals with fast processes, such as voltage and frequency control, which also affect MG stability. Due to the time-critical requirements of the informational exchange for equal power sharing among the MG units, a communication-less approach is usually adopted for the primary control. For this purpose, droop-based control techniques and virtual synchronous generators (VSG) are the most effective methods, which, by simple yet effective mechanisms, provide voltage and frequency control. The disadvantages are that these mechanisms cannot restore the two grid parameters to the nominal values and can only be used in islanded operation mode [11], [18]. Another solution used in the past, mainly for paralleling inverter units in systems with uninterruptible power supplies [19], is based on a master-slave method and a high-speed communication network [20]. Although it achieves excellent power-sharing performance with a simple control algorithm, the expansion of master-slave control to complex MGs is limited by the requirements of high-bandwidth communication networks [21]. Maintaining system stability requires communication latency in the range of milliseconds, but this latency range is variable in time [22] and difficult to ensure in large-scale MGs [21], [23].

Several other communication-less methods are proposed in the literature to achieve power sharing in MGs. In [24], a voltage-frequency bus-signaling method is developed to coordinate the operation of distributed energy resources (DERs) within an islanded MG. However, extending the proposed solution to complex MGs is difficult to achieve. In [25], they developed a power flow control strategy for off-grid networks using the various patterns of frequency change rate as a communication agent in a small-scale MG based on Photovoltaic (PV) inverters. Although the solution does not have a defined multi-level control structure, it can be considered as a primary control since the frequency change instantly triggers the controlled units to change their output power.

B. SECONDARY LEVEL

The secondary control ensures the restoration of electrical parameters (voltage and frequency) to the required values. Within the same control, seamless grid connection or

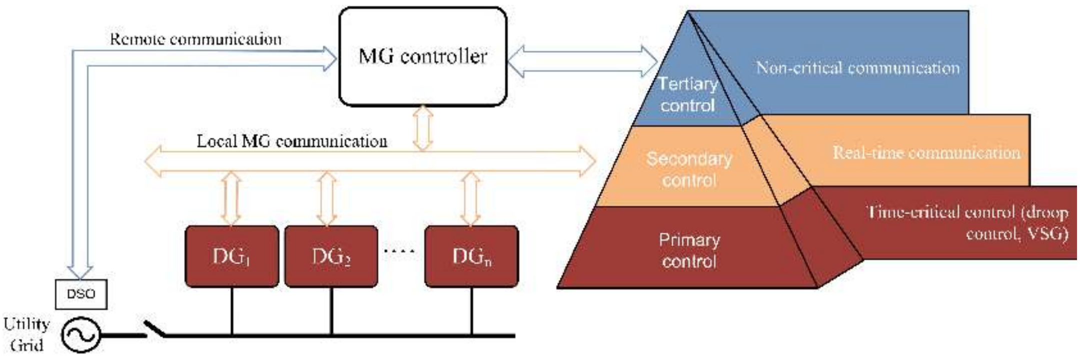

FIGURE 2. A hierarchical view of control levels in MGs.

disconnection may also be implemented. An overview of the main existing secondary control methods is provided in [26], in which the authors classify the methods into three categories: centralized, distributed, and decentralized secondary control. Whereas the centralized and distributed methods require exchange of information between units through a communication network, in the fully decentralized approach the restoration process of voltage and frequency is carried out by multiple secondary controllers operating locally at each distributed generator (DG) without data sharing with other DGs [27], [28]. Communication-less control may provide some important advantages; however, these decentralized secondary control methods must overcome a variety of issues such as clock-drift [29], [30] to reach the maturity level of the centralized and distributed solutions. For our purposes, then, only the two secondary control categories based on communication will be included in this investigation.

The most effective implementation of this control level is based on a low-bandwidth communication system, which allows voltage and frequency correction signals to be sent from a centralized controller [31]–[33], or using a distributed approach with the information transferred by means of neighboring agents [34]–[38]. The speed of communication directly affects the performance of secondary control and, therefore, a trade-off between bandwidth and transitory response is usually required [39].

The most mature solutions are based on a centralized MG controller, which provides reference correction signals for voltage and frequency restoration within the secondary control, as represented in Fig. 3. In this centralized control system, the transmitted data packet is typically sized for two reference signals (i.e., one for voltage and one for frequency) [32]. However, some control methods require several other signals for controlling the MG when grid synchronization is also carried out by the same mechanism [33], [40], [41]. One control method with a minimalist low-bandwidth communication infrastructure ensuring both secondary control and grid synchronization is proposed in [42], where the data packet transmitted from a central controller to the MG units does not change with the operating state (i.e., islanded or grid-connected).

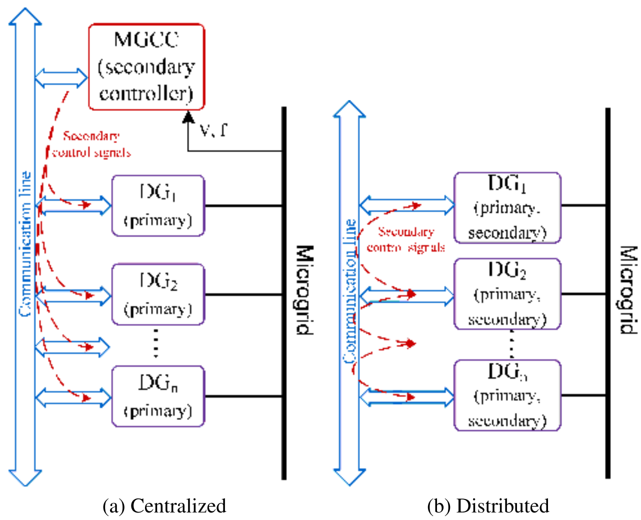

FIGURE 3. MG secondary control.

In the traditional centralized secondary control, the central unit collects all the information from each generator and then sends signals back, such that the communication volume increases proportionally with the number of control units. However, in an optimized version of a centralized secondary control, a minimum number of signals are required to be sent through the communication network, and that number remains unchanged with the increase of MG complexity [42]. The problem with the centralized control approach, however, is that it is prone to failures, in which case the whole system may collapse. To overcome this situation, distributed secondary control methods have been proposed in the literature.

The distributed approach requires data to be sent from one unit to another without a central coordination, as illustrated in Fig. 3b. The distributed control typically requires each control unit to exchange information with its neighbors, the communication requirements varying from sending and receiving measurements (e.g. active/reactive power, voltage, and frequency) to and from all direct neighbors [43], to optimized solutions that reduce the communication burden to only selected neighbors [37].

In [44], a distributed control solution integrates the secondary controller in each DG together with the primary controller. The secondary controller in each DG receives three measurements (frequency, voltage, and reactive power) from all the other DG units through the communication system and computes the secondary correction signals, which are passed to the primary control. With this approach, the failure of one unit does not affect the rest of the system; however, a centralized controller is still required for some particular functions, such as black start operation and MG resources management. This approach, then, can be considered a mixed solution instead of a purely distributed control solution. Although the proposed solution eliminates the issues related to relatively low reliability of the conventional centralized control, the burden of communication can significantly increase when MGs increase in complexity.

Other approaches based on multi-agent systems also implement distributed control solutions. In [36], a control method based on a sparse multi-agent communication network is proposed to overcome the centralized control deficiencies, therefore, improving the system's robustness and flexibility. In [45], the authors proposed a multi-agent system for distributed power sharing in an islanded MG. Based on an algorithm, the system discovers the global MG information required for equal active power sharing among the MG units, exhibiting reduced communication requirements. Similarly, a two-level control structure for multi-MG systems improved the dynamic performance in [46]. The agents are interconnected by low-bandwidth communication links, transferring data to a limited number of neighboring agents and, therefore, significantly reducing the communication burden. Within the secondary controller, a fast power limiting strategy is implemented to prevent overloading the MG generation units. However, the control parameters are dependent on the transmission rate required between agents and through the communication line, thus limiting the system performance and its stability margin [34], [37].

C. TERTIARY LEVEL

The MG energy management system (EMS) is usually implemented at this level (tertiary), and it involves non-critical tasks required for power flow optimization in the MG. The EMS decisions regarding optimal scheduling of MG resources are provided by a centralized system at a low sampling rate (several seconds or minutes), where low priority data packets are transferred through the MG communication network.

When MGs are connected to the grid, the tertiary control level manages the power flow between the MG and distribution network, according to power references provided by the distribution system operator (DSO); hence, a communication link between the EMS and the DSO has to be implemented [47]. In a multi-MG system, such as the one represented in Fig. 1, the tertiary communication layer is also used to provide information exchange between neighboring MGs [48], [49].

D. MG SYNCHRONIZATION

Probably one of the biggest challenges for the growing area of MG development is the method of MG synchronization with the grid and the communication system that can best achieve this. Providing an automatic grid transfer mechanism represents one essential feature of an MG, but ensuring the system's stability during and after the self-transfer between the MG operating modes (i.e., grid-connected and isolated) implies significant challenges. Moreover, the seamless transition becomes more difficult as the number of units involved increases [35]. Traditional synchronization methods are not generally suitable for such complex systems [31].

Of the three main synchronization methods, i.e., active, passive, and open-transition, identified in [50], the active synchronization control is of particular interest because it allows higher operational flexibility and performance. However, as highlighted in [50], the active methods do require special control data transferred through the MG communication infrastructure, which is usually fulfilled within the secondary or tertiary control mechanisms presented above.

The literature describes various active methods to achieve synchronization between the MG and the grid [42], [51], [52]. In [42], the MG synchronization to the grid is implemented within the secondary control layer. In the solution, data packets are transmitted through a Controller Area Network (CAN) and have the advantage that their size remains unchanged regardless of the MG operating state and the number of inverters. In [51], the authors propose a multi-MG system where the synchronization of the isolated MGs into a cluster is carried out by means of a long-distance communication infrastructure based on Wide Area Network (WAN) technology. As shown, the selection of the sampling period of data transmission from MGs to a central controller sets up a trade-off between the sampling period and the capabilities of charging/discharging of energy storage systems. In [52], the authors proposed a decentralized grid-synchronization approach based on self-organizing agents communicating in a local network, which is claimed to be less vulnerable to communication link failures. However, there are no quantitative indications about the method's robustness against various communication problems that may occur in a practical application. In [33], the authors address the challenge of accurately matching the MG voltage to the grid voltage (in terms of instantaneous values). They propose a MG synchronization method that uses a low speed communication network to broadcast, from a secondary centralized controller, to the primary controllers of each inverter the fundamental positive and negative sequence components, as well as the harmonic components.

Despite the various methods proposed to achieve MG synchronization to the grid, the main challenge continues to be how to coordinate multiple inverters to seamlessly and precisely match the grid instantaneous voltage at the moment of physical connection (i.e. main switch closing).

III. MG ARCHITECTURE-RELATED COMMUNICATION REQUIREMENTS

The building blocks of the future Smart Grid will be the highly-automated smart microgrids (S-MG). These will require a fast and reliable communication system to control MG internal functions and be able to network the control center with each component of the system (if such a solution is considered) or between the local controllers in the case of a distributed control scenario. To compare performance, it is important to identify characteristics of the communication system, such as data transmission requirements, transmission media, protocols, and standards that will directly impact the operation of the MG and S-MG.

S-MG systems are known to be highly vulnerable to cyber-attacks, especially in scenarios in which the manipulation of information represents economic profit. Because of this threat of attack, the communication networks of S-MGs require networking and security tools, such as virtual private networks (VPN), firewalls, encryption protocols, or blockchain platforms. Although cyber-security and its impact on S-MGs are important topics, an in-depth discussion of those aspects do not fall within the paper's scope. However, the technologies and network architectures considered in this manuscript are generally compatible with security solutions reported in literature. For further information regarding cyber-security concerns in power systems and S-MG, we suggest checking the works discussed in [53] and [54].

A. DATA CHARACTERIZATION AND TRANSMISSION REQUIREMENTS

Four main functions are necessary to accomplish proper MG operation: advanced monitoring and control (AMC), system protection (SP), demand-side management (DSM), and generation and storage management (GSM) [55]. Depending on the MG structure and operation requirements, some of these functions can be deployed within the EMS [56].

Data for managing each of the functions is sent by the communication network as data packets with specific sizes. The size of the data packets in the communication network of an MG is confined between 32 and 200 bytes [57] if the data is encoded for the IEC 61850 protocol. Real world data such as voltage and current measurements, as well as breaker and disconnect switches status, are also converted from signals into data packets with sizes around 15 bits (circuit breaker) and 27 bits (power measurements) [48]. Some data such as protection information data are essential and critical for the safety of the MG and require small latency and no data loss. Noncritical measurement data, such as data related to the EMS within the tertiary control level, require less accuracy in terms of latency and reliability. More precise restrictions in terms of packet latency are shown in [56], [58]–[61] and illustrated in Table 1.

It should be noted that although IEEE, IEC, and ETSI standards define general frameworks for S-MG controllers, the IEEE 2030.7 standard classifies the control objectives (such as voltage and frequency regulation, power control, synchronization, energy management, etc) in four blocks, and defines a response time for each block (see Table 1). Taking into account MGs state-of-the-art control schemes, the IEEE standard also considers that the control objectives established for these blocks can be deployed into device controllers, plant controllers, and MG controllers. Then, primary and secondary control levels, as defined in Section II-A and II-B respectively, can be placed in device controllers (e.g., distributed schemes). In this case, the role of the communication network is to allow information sharing among the controllers to achieve the objectives of the secondary level. When secondary and tertiary control levels are placed together in an MG controller (e.g., centralized schemes), the MG is more susceptible to communications issues. In any case, the primary level always requires a faster transmission data-rate and lower latency, as shown in Table 1.

B. COMMUNICATIONS NETWORK ARCHITECTURE AND TRANSMISSION MEDIA

The MG field elements, such as RES (e.g., PV, wind, and Hydro), storage facilities and loads, exchange information (i.e., signals) amongst them and also with control elements in the form of data packets. The communication networks transporting the signals can be wired or wireless. The most representative technologies used in S-MGs are summarized in Table 2, considering their advantages and disadvantages.

Signals inside the MG elements, such as power electronic converters, their primary controllers and measurement devices, typically travel through wires, optical fiber, and unshielded/shielded copper twisted pairs (UTP/STP), in relatively close contact with each other. However, the communication signals that move among the different types of MG equipment, such as DGs or secondary and tertiary controllers, usually use power line communication (PLC) and wireless technologies. Several features, such as protection against strong parasitic electromagnetic fields, scalability, data losses, and operation-and-maintenance cost, are considered as inputs for the cost-benefit ratio for selecting the proper communication technology.

Implementation and maintenance costs impact the cost-benefit ratio for optical and twisted pair networks because these technologies require dedicated ducts and connectors to ensure good performance, whereas PLC modulates and sends the data frames through the power lines, reducing the implementation and operation costs. The main disadvantage for UTP/STP networks is the reduced coverage (100 m) per wire section when transmission control or user datagram protocols (TCP or UDP) are used. Though using serial protocols, such as RS232 or RS485, the coverage distance can be increased, such protocols introduce compatibility and failure diagnosis issues to the networks. Moreover, PLC is a restricted technology because to scale this type of network,

TABLE 1. Data transmission requirements for S-MG functions [56], [58]–[61].

IEEE 2030.7		Maximum Latency Requirements		
Control Block	**Action time**	**Task**	**IEC 61850**	**ETSI Open SG Protocol**
1	sub-sec to 5-10 min	Protection	4 ms	1-10 ms
		Control	16–100 ms	100 ms
		Messages requiring immediate actions	1A: 3 or 10 ms 1B : 20 or 100 ms	not specified
2	few sec/min	Time synchronization	Accuracy	not specified
3	5-10 min to 1 day	Monitoring	1 s	1 s
4	5-10 min to 1 week	Operation and maintenance	1 s	not specified

beyond indoor environments, is more expensive than other wired technologies mainly because data frames cannot be propagated through transformers [58].

Wireless channels are more versatile than wired ones because they are economically viable, reliable, and scalable by simply including new nodes and routers with no additional installation of cables. Cellular networks (3G, 4G, and soon 5G) are robust technologies but operate in licensed radio frequencies; hence, the use of these technologies by third party facilities implies an expensive operation cost [62]. Therefore, technologies such as Wi-Fi or ZigBee have a better cost-benefit ratio. However, because these wireless technologies use unlicensed frequencies, they are more susceptible to interference, line of sight requirements, and security issues, which may result in a high variance in latency and data losses [63]. Similarly to wired channels, the coverage of wireless systems depends on the technology used. With Bluetooth, coverage can be limited to a few meters, whereas with WiFi, it can be about 100 meters (Long-range WiFi is possible using specific hardware, but it is currently unregulated). An additional issue regarding wireless networks is the penetration capability. Technologies that operate in lower frequency bands will have a higher penetration, which is important for microgrids that operate in highly obstructed environments, e.g. mountains or cities.

Recently, a new category of low-power wide area networks (LPWAN) has been explored as an alternative wireless solution for smart grid connectivity, and in some cases suggested for MGs [64]. LPWAN technologies such as LoRa, Sigfox, and NB-IoT can provide a wide coverage (sometimes wider than a base station in a cellular network) at low implementation and operational costs. Nevertheless, existent studies only discuss the potential implementation of LPWAN technologies by assessing their coverage, data rate, and energy consumption in more generic scenarios, without specifically evaluating their suitability to fulfill the MG control requirements [65]–[67].

In Table 2 we provide the technical details of the different wired and wireless technologies suggested for MG communications, identify the advantages and disadvantages of each technology in the context of MG's deployments, and define the suitability of the communication technologies according to the MG control levels. The suitability we suggest depends on several aspects such as the control topology, geographical location of the MG, and funding available.

Wired technologies, except for PLC, are suggested for primary and secondary controllers. For the primary level case, short distances among hardware control, measurement devices, and power electronics converters should be covered, ensuring low latency and higher reliability. Since the primary level does not consider special scalability requirements, optical and twisted pair channels satisfy the communication requirements successfully. When distributed schemes are used, and primary and secondary controllers are deployed in different devices, the communication between these devices has the same requirements as the communication between the primary controller and power-related hardware. In addition, when secondary centralized schemes are used, the distance between the primary and the central controller, as well as the expected scalability, should be considered in the deployment of wired technologies.

Considering a scenario where networking devices and features, such as routers, access points, firewalls or virtual private networks (VPN) are used properly, WiFi networks for exchanging information among secondary controllers may be recommended. Since the latency in these wireless networks is around tens or hundreds of milliseconds, it is possible to achieve a proper secondary control response in a few seconds, as established in [56]. Although the features of cellular-based networks are completely feasible for exchanging information among secondary controllers, these technologies become expensive when the service agreements are defined to ensure the quality of service required. Additionally, the cellular networks are not always available in rural areas where many MGs are expected to be deployed.

The application of emergent 5G technologies in MGs requires further analysis. Although 5G has a wide spectrum of uses in urban environments, the use of 5G technologies in rural/remote places is still quite expensive. If high frequency bands are employed, the transmission in mm-wave requires

TABLE 2. Communication technologies applicable in S-MGs [59], [62], [68]–[71].

Type	Technology	Maximum Coverage	Rate	Frequency Band	Advantages	Disadvantages	Suitability
Wired	Optical Fiber	100 km	10 Mbps (IEEE802.3j) to 100 Gbps (IEEE802.3cd)	Near-infrared and visual spectrum	-High speed -Low Interference -Low Latency	-Expensive Technology -Complex scalability -Expensive maintenance	Primary and secondary control
	Twisted Pairs	100 m	10 Mbps (IEEE802.3i) to 10 Gbps (IEEE802.3an)	<25 MHz <500 MHz	-Easy access -Easy configuration	-More capabilities-more cost -Complex scalability	Primary and secondary control
	Power Line	200 m	14-200 Mbps (IEEE 1901	<100 MHz	-Low implementation cost -HomePlug compatible)	-Fixed topology (non-flexible) -Complex scalability	Tertiary control
Wireless	Wi-Fi	100 m	11Mbps (IEEE802.11b) to 10 Gbps (IEEE802.11ax)	2.4 / 5.9 GHz	-Cheaper technology -Easy configuration -Easy scalability	-Susceptible to interference -Higher cost with increased security	Secondary control
	ZigBee	100 m	250 Kbps (IEEE802.15.4)	2.4 GHz (2006)	-Cheaper technology -Low power consumption	-Low speed	Tertiary control
	Bluetooth	100 m (class 1)	1 Mbps (IEEE802.15.1-2005)	2.4 GHz	-Cheaper technology -Low power consumption	-Low penetration -Security issues	Tertiary control
	Cellular 3G	50 km	<2 Mbps	800/ 850/ 900/ 1800/ 1900/ 2100 MHz	-Designed for data packets transference -Third party facilities	-Expensive operation cost -Expensive QoS	Tertiary control
	Cellular 4G	50 km	<100 Mbps	2600 MHz	-Designed for Internet access -Third party facilities	-Expensive operation cost -Expensive QoS	Tertiary control
	Cellular 5G	50 km	<10 Gbps	sub-6 GHz and mm-Wave frequency bands	-Designed for Internet access -Very low latency	-Non-wide facilities -Emergent technology	Tertiary control
	LoRa	5 km (urban), 20 km (rural)	<50 kbps	433/ 868/ 915 MHz	-Low power consumption -High penetration -Easy scalability	-Low speed -Restricted downlink	Tertiary control

several hot-spots to improve coverage and overcome line-of-sight obstacles, increasing as well the maintenance and operation cost for third-party providers. In this case, WiFi has advantages over 5G technologies, considering that private and low cost WiFi networks can be deployed and the coverage can be improved using directional antennas [72], [73].

Urban environments allow proper applications of 5G technologies in MGs, specifically the ones based on the ultra-low latency and reliable communication (ULLRC), and massive machine-type communication (mMTC) features of 5G. Although the technology developed under the ULLRC standard satisfies the requirements of S-MG secondary control applications, this standard was developed to cover critical-mission communications, and its use could be regulated in the future. The mMTC standard was developed for industrial IoT applications with massive deployments in terms of number of connected devices; hence, low data-rates are expected to preserve the network reliability. These features make mMTC applications proper for tertiary control in microgrids [74].

TABLE 3. International standards for MGs communications and networking [47].

Reference Standards	Detail	Application
IEC 61850 (61850–7-420)	Communication between devices in transmission, distribution, and substation automation system	DER/microgrid
IEC 61968	Data exchange between device and networks in the power distribution domain	Energy management system
IEEE 1547.x	Interconnecting DERs with Electric Power System	DER/microgrid
IEEE 1646	Communication Requirements	Substation Automation

Technologies such as Zigbee, Bluetooth or PLC perform well in indoor environments and can exchange information among intelligent devices usually used in homes or offices making them suitable for the tertiary control level. At this control level, the messages within the communication network are focused on microgrid management and coordination, therefore reliability and latency requirements are lower than for the primary and secondary levels. These technologies and also LPWAN (e.g., LoRa) for outdoor environments allow logged information to be sent from the intelligent devices to the tertiary controller, which is used as input to forecasting models or load management.

Within the literature, communication networks are broken into several categories, presented below in relation with the S-MG concept. Customer networks are those covering home area networks (HAN), industrial area networks (IAN), and building area networks (BAN). These networks are connected to an external Neighborhood Area Network/Field Area Network (NAN/FAN). HAN mostly include home automation appliances and smart meters, but may also include small energy sources (PV and small wind turbines) and home storage units. IAN and BAN are more complex networks with a large number of control devices and sensors for building and industrial EMS and Supervisory Control And Data Acquisition (SCADA) systems. Customer networks require low data rates and low power consumption, scalability, and security of connection, for which various communication technologies can be implemented [75].

NAN/FAN networks are used for communications (and control) at the distribution substations level as well as for control of data flows between the WAN and the customer premise networks. These types of networks provide a large number of S-MG services, such as smart metering from customer sites to the control center, load management, and distribution automation. Typical data flow rates can vary from 100 kbps to 10 Mbps covering distances between 100 m and 10 km [75].

The communication technologies in WAN deployments (e.g., cellular and passive optical networks), provide wide geographical coverage for MGs, enabling the communications between the control center and the transmission and distribution substations, for EMS and updated SCADA systems. The MG's WAN may comprise a large number of communication nodes, including smart meters, remote terminal units (RTU), phasor measurement units (PMU), and other sensors for remote automation purposes. For example, an MG's WAN based on a passive optical network can ensure reliable, fast, secure, high-speed, and real-time exchanges with virtually no data losses. However, the costs involved in creating wide area optic fiber networks and the further expense involved in subsequent expansion may make the recent generations of wireless technologies the preferred option for long distance coverage and high data flow rate needs.

An important quality of wireless networks is their capability to easily change from infrastructure-based to ad hoc communications. By replacing a network controller as a single point of failure with ad hoc communications, the reliability of MGs is increased. Nevertheless, given that security is a growing concern, there are recommendations [55], and field implementation examples [76] that use two separate communication networks in S-MGs: one for communication control and the other, physically or logically separated, for the telemetry/data acquisition service network.

The topology of the communication networks does not need to be identical with the power network. Different topologies have been employed in wireless networks to improve the speed, redundancy, and reliability, and avoid traffic congestion and packet losses. Some well-known topologies for communications are the bus, star, ring, mesh, multi-hop and hybrid networks. For S-MGs that must cover a wide geographical area, the best solution identified in [57] in terms of end-to-end delay and throughput communication performance has proven to be, at a close distance to the alternatives, the hybrid star-ring topology. However, more complex network topologies may be required to ensure redundant paths in case of link failures.

C. COMMUNICATION PROTOCOLS AND STANDARDS

The recommended/used communication protocols can be separated in those specifically developed for MG applications, such as Modbus, DNP3, and IEC 61850 series of standards, and those that were initially designed for other purposes, such as the Internet Protocol Suite (IP, TCP, NTP). Further details regarding standards and fields of application are given in Table 3 [47].

As the communication network in an S-MG is a hybrid, efforts are made by equipment suppliers to build compatible solutions between communication protocols. In the same way, in [57], the authors reported IEC 61850-based design and modeling of IEDs for different types of distributed energy resources and a new logical node for controllable loads along with the design of structure and size of communication messages required for energy management automation in a microgrid; this is also to demonstrate the capabilities of IEC 61850 standard for MGs.

IV. IMPACT OF COMMUNICATION NETWORK PERFORMANCE ON MG OPERATION

The performance of the communication network is critical in achieving the objective of building the future smart grid with interconnected microgrids, as highlighted in Fig. 1. Key issues include ensuring interoperability among various communication technologies and protocols (such efforts have already been made with the new version of IEC61850), developing resilient MG control solutions with increased robustness to communication failures, and enhancing the security of communication in MGs. To address the impact of communication network performance on MG operation, this section reviews theoretical approaches and practical implementations that consider the effects of the communications network on the general performance of the MG and provides insights into the proposed technologies (wired and wireless) that can support the communication requirements in MGs.

A. THEORETICAL APPROACHES

By describing the communications infrastructure of a microgrid, we can study how the usual network problems, including packet loss, packet latency, and jitter, can affect the performance of an MG. The approaches presented in this section introduce the network parameters in the theoretical models either as deterministic [1], [77] or probabilistic variables [78]–[80]. Some of these works are not based on any particular communication technology or protocol; instead, they provide a generic theoretical description to understand MG behavior under different operating conditions of a communication network.

1) DETERMINISTIC NETWORK PARAMETERS

In [1], the authors study voltage and frequency control in an MG system that incorporates a communications network. They define a hierarchy of a communication control system. A follow-up work focuses on how to design the control mechanisms over voltage and frequency on the secondary control level [77]. Although the authors do not specify which communication protocol they use for measuring data traffic, they do define packet loss and packet latency as important network parameters to analyze the effects over power control of the whole system. An algorithm is proposed to operate on the distributed generation level, which compares average local sensed data with average global sensed data and then tries to converge to that global average. They simulate an MG network using *MATLAB* and its toolboxes, using predefined packet loss and latency values and connecting and disconnecting loads abruptly to the MG to analyze whether voltage and frequency control can be achieved and to what extent. The results show that packet latency in the network has a negative impact on how the system reaches frequency and voltage stability by lagging the system's response after a sudden load change. To evaluate the impact of communication in a severe perturbation scenario, in [77] the authors have applied a broadcast packet loss probability of 95%, which makes the communication practically nonexistent. Although the dynamic response is considerably affected, the system reaches steady-state operations. When the communication is completely broken in the distributed generation, it makes the frequency and voltage levels drop to undesired values without returning back to normal levels.

2) PROBABILISTIC NETWORK PARAMETERS

Real wireless communication networks have time varying packet latency between different elements within the network; therefore, it is important to analyze how this phenomenon impacts the MG. Inverters are needed to convert DC current to AC, which is important for the majority of MG, so coordination between the inverters in the network must be addressed in order to have the same frequency and amplitude operation. This issue is studied in [78], where a simple two-inverter simulation compares time varying packet latency between the inverters and a mesh topology. A unified Smith Predictor [79] controller is proposed using the information of the delayed packets. Results show that time-varying packet latency affects both the amplitude and frequency of the whole system when comparing a system with the controller implemented and others without it. Power loss is also drastically increased if packet latency is not mitigated. The authors do not mention any specific wireless technology as part of their study.

An algorithm for MG state estimation is provided in [80], which incorporates packet loss and noise. The model considers a discrete MG state where the wireless channel is modeled as a source of noise and packet losses by defining a *gaussian* distribution with zero mean and a packet loss parameter, respectively. An estimation algorithm is then implemented by using least mean square fourth, which simplifies the estimation process. A simulation sets predefined values for the *gaussian* noise and the packet loss parameter and shows that the proposed state estimation converges more quickly if no packet latency is present. The author does not refer to a specific wireless technology but mentions that a digital modulation, BPSK, is employed.

Another MG algorithm is presented in [81], which the authors define as a discrete-time linear state-space algorithm incorporating packet losses. A remarkable aspect of this work is that it incorporates a distinct analytical description between power sources, energy storage systems, and loads. To analyze packet loss phenomena, a *Bernoulli* distribution model is incorporated to the system. An adaptive-then-combine diffusion *Kalman* filtering algorithm is obtained by minimizing the estimation error covariance matrix of the local estimators. With the *Kalman* filter defined, the authors made a simulation with four sensing stations sending information in a broadcast fashion, and using predefined, non time-variant parameters for the whole system. The system gives good results due to a fast converging estimated state to the real state of the MG in the presence of packet losses.

B. SIMULATIONS AND EXPERIMENTAL/PRACTICAL IMPLEMENTATIONS

1) WIRED TECHNOLOGIES

Wired technologies, including copper-based and fiber-optic cables, have been quite popular for MG communications infrastructure. A number of studies describe the use of Supervisory Control And Data Acquisition (SCADA) systems for sensing and controlling. In such scenarios, different kinds of wired technologies are mixed.

One of the defining characteristics of an MG is its ability to operate disconnected from the mainstream electrical grid. Lázár *et al.* [82] provide an implementation of a SCADA system for data acquisition in an MG. The wired communication technology operates over the *RS485* standard because it is a multipoint system employed in electrical noisy environments over small to medium distances. Although this work defines an algorithm for data acquisition and control, it does not determine how the network's performance behaves in the presence of bidirectional communications.

Another work tackling the islanded mode of operation of an MG is presented in [83]. The architecture considers a mix of RS485, CAN bus, and Ethernet. A network architecture is proposed to deal with generators, loads, batteries, and switches that can be remotely controlled using both RS-485 and Ethernet. CAN bus is used for the management of batteries in the system. Similar to [82], this is a technical work for implementing a real control infrastructure for MGs; however, unfortunately it does not show how the implementation deals with packet latency or packet loss.

Another extensive implementation work is described in [84]. The authors clearly define how they will forecast energy activities in the grid and provide an algorithm to make control decisions and perform analysis on readily available energy data. The idea is to communicate different DERs for real-time data exchange. This is done by using technologies like Ethernet, RS485, and IEEE 802.15.4. A more generic, total output power model for the MG is presented, where each type of MG hardware (battery, load, and generator) is modeled differently. The work considers both islanded and non-islanded modes. The experiments show that the system is able to manage energy efficiently. This work in particular is noteworthy for its detailed explanations about the implementation, including information of electrical and communications equipment.

The work presented in [85] is more focused on a controller between several MGs, but it involves communications to perform such a control. This implementation employs a central Linux machine for control of a power park, which is composed of several MGs. It is different from much of the MG communications research because it ignores HAN or NAN communications between components; instead, it focuses on the WAN for the control purposes. Using different MGs as part of an interconnected system can provide a more reliable power network as neighboring MGs can work as backup power for each other. A CAN bus based communication technology is implemented in this case. This work expands the control challenges of an MG, even defining different hierarchies of control (primary, secondary, and tertiary), but it lacks details on implementation and results. A comparison of MG power management with and without the controller is necessary for completeness.

2) WIRELESS TECHNOLOGIES

Among the wireless communication technologies, IEEE 802.15.4 is proposed as a a low power, versatile solution to the MG communication infrastructure problem [86]. Although there are not many reported implementations of real MG communications based on ZigBee (a proprietary technology that uses IEEE 802.15.4 on the lower layers of the communications stack), the work described in [48] offers a good starting point for understanding ZigBee as applied to MGs. It starts with a comparison of the most promising wireless technologies for MGs and then lists all the advantages of using ZigBee for this purpose. It proposes a hierarchical communication framework for all nodes in the network and different modes of operation, which means that some nodes work as coordinators whereas others just receive and send data. A numerical analysis is provided considering the following parameters: the size of every packet to be handled, the use of three different carrier frequencies available in ZigBee, and the number of nodes in the network. All this information is employed to obtain the data transmission delay. The results show that an increasing number of nodes in the network along with slower carrier frequencies have a negative impact on the performance of the MG.

X. Zhang *et al.* [87] present a Non Technical Loss (NTL) analysis incorporating packet loss on an existing MG, which uses another proprietary communications protocol based on IEEE 802.15.4. The communications technology provides a mesh topology and a time-synchronized sampling for the 525 nodes used for power delivery. By using the data gathered from the network, the authors create an NTL model and then an NTL detector based on Support Vector Machines to handle power loss alarms automatically. The work gives data about packet loss, but the authors deem that this parameter can be safely ignored because of the reliability of the grid.

A simulation of an MG is carried out in [88] using an *Opnet Modeler* to study how latency and throughput behave on three different topologies: star, tree, and mesh. The simulation results show the mesh topology has the best latency and the worst throughput, contrasting with the star topology with the worst latency and the best throughput, and the mesh topology in the middle ground. Further analysis is carried out by changing the number of nodes in the grid, showing that an increase in this number harms latency and particularly throughput in the whole network. This work simulates transmissions between nodes with and without obstacles and shows how the Received Signal Strength Indicator (RSSI) changes accordingly.

In [89], a hybrid wireless communications network is simulated by incorporating ZigBee, WiFi, and WiMAX for hierarchical communications between components of the MG. For simulation purposes, a power generation/flow model is employed for the different types of elements in the power network, including wind turbines, photo-voltaic panels, and batteries. A wireless technology overview is then presented, defining which technologies are best for HAN, NAN, and WAN applications, where ZigBee, WiFi, and WiMAX are used respectively. Islanded and non-islanded controls are described, and an algorithm for power management and control is proposed.

3) STUDIES ON COMMUNICATION LATENCY OVER MG CONTROL PERFORMANCE

An unavoidable effect of communication used in the control mechanisms of an MG is the inherent latency and propagation delay of data transmission, which generally reduces the control performance and may also affect system stability. In [36], the analysis of communication latency's influence on the convergence of the control algorithm in an MG shows how exceeding a certain latency threshold, which is in the range of several milliseconds, affects the speed and stability of the system control. Similar conclusions emerge from a more focused study in [22] on the impact the communication latency has on secondary control in an MG. The investigation targets the analysis of stability limits with the gain variations of a centralized secondary controller (usually a PI controller is used) and communication latency, and by means of a gain scheduling approach, it improves the robustness of MG secondary control to communication latency.

On the same subject of secondary control for islanded MGs, a distributed control strategy with consideration of time latency and data drop-out limits of the communication systems is proposed in [44]. Experimental results have shown that the distributed controller ensures higher robustness in front of large communication latency (up to 1s) and data drop-out (more than 50%). A distributed control scheme designed for secondary voltage and frequency restoration in autonomous MGs is described in [46], where the involved control units are interconnected through a sparse communication network of reduced bandwidth. The proposed distributed architecture of agents reduces the communication burden, as each agent only communicates with a limited number of neighboring agents. Moreover, the analysis reveals the influence of communication delay on the system dynamics, observing that as the delay is increased in the range of tens of milliseconds, the system becomes more oscillatory until the stability limit is reached.

Gomez et al. [38] also studied islanded MGs. They showed the effects of communication latency, data dropouts, and topological changes on the communication network, using distributed secondary predictive control validated with an experimental setup. They found the predictive control was able to compensate for typical communication issues experienced by the system. Increasing system robustness against large variations in communication delays was the subject of [90]. They implemented a Model Predictive Control (MPC) for the secondary control of MGs. They then compared the MPC with a Smith predictor and a conventional PI control showing that, while it is considerably more robust in terms of maximum delay, the MPC strategy has slightly lower dynamic performance than the conventional PI controller; also, in [90] the authors consider a stability analysis based on small signal models. Since the islanded operation poses more stability issues than the grid-connected one, most studies about communication impact on MG control performance are focused on this regime.

An analysis of the influence of communication delay on system performance for both operating regimes is provided in [42]. It is shown that during grid-connected mode, the maximum delay is higher than in islanded mode, while the transfer regime between the two modes, during which the synchronization process of the MG with the main grid takes place, significantly reduces the allowed communication delay at which the system reaches its stability limit. An important point worth noting is that the maximum communication delay is highly dependent on the control parameters, meaning that it is possible to maintain the system's stability for a certain communication latency by a proper selection of controller parameters, i.e. a trade-off between communication delay and control performance is usually required [39].

V. EXPERIMENTAL ANALYSIS ABOUT COMMUNICATION IMPACT ON MG PERFORMANCE

Although the number of studies regarding secondary control in MGs continues to increase, with the most relevant ones analyzed in this paper, experimental evidence of the communication impact on MG performance with emphasis on comparative analysis of different communication technologies has yet to be provided to the best of our knowledge. Therefore, the discussion in this paper about communication requirements in MGs and available communication technologies is enriched with an experimental analysis of the impact of communication on the secondary control provided in this section. For this purpose, a complex laboratory MG with two communication networks (wired and wireless) was used. As shown in the block diagram from Fig. 4, the MG consists of three 5 kW inverters, each being controlled by an independent dSPACE DS1103 real-time controller. Each inverter controller has the capability of switching between the wired and wireless communication networks. An illustration of the laboratory setup is presented in Fig. 5, while details about the specific MG control employed and the hardware structures can be found in [42].

As highlighted in Fig. 4, on the communication side, the first option is for the controllers to exchange information through a CAN bus operating at a transmission rate of up to 1 Mbps with a default speed for the experiments provided in this paper of 500 kbps. To evaluate the MG behavior when

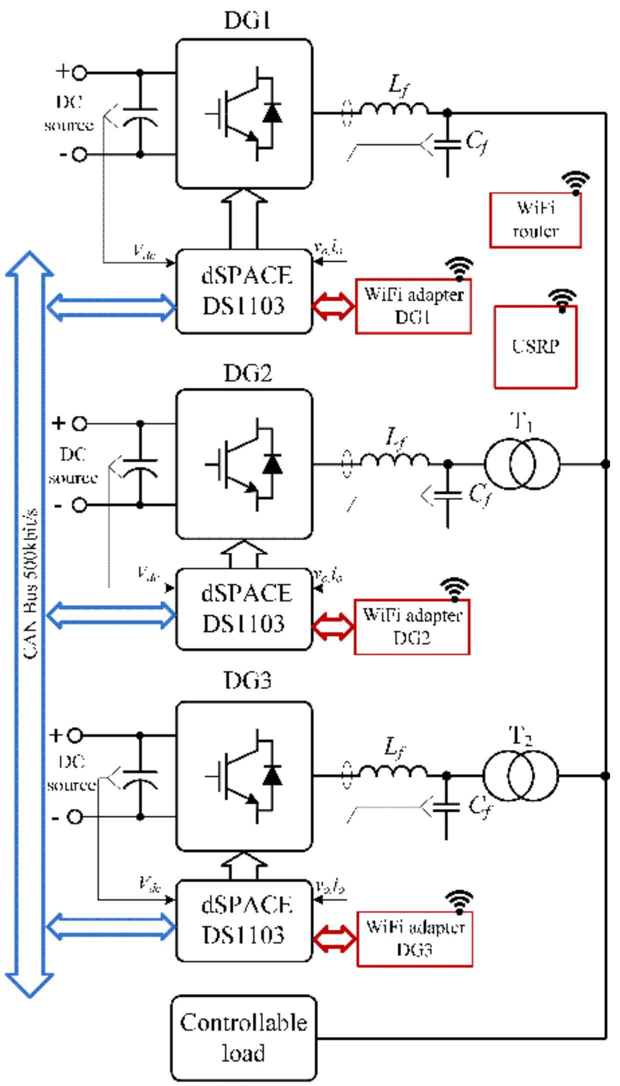

FIGURE 4. Diagram of the experimental MG.

connected via wireless communications, the system has been updated with a second option of communication using a WiFi network. The use of WiFi as the communication technology for MG secondary control has already been considered by other researchers [28] and is one of the technologies described in Table 2. Wireless communication technologies represent a solution of high interest for the future implementations of MGs because of their superior cost-performance ratio in comparison to wired solutions. Moreover, because wireless communication is more prone to disturbances and failures, it provides a more challenging scenario to test the MG secondary control performance, as demonstrated by the WiFi experiments described hereinafter.

The secondary control of the MG analyzed requires sending a packet with two signals (associated with voltage and frequency correction), which comes from a leading inverter and broadcast to all the other DGs within the MG. The signals are sent in a single-precision format so that a message includes 8 bytes of actual data integrated into the communication protocol frame format.

TABLE 4. Literature review on maximum communication delay for secondary control in islanded microgrids.

Reference	Maximum communication delay [s]
[22]	0.2
[26], [28]	0.6
[37]	1
[38]	0.5
[42]	2
[43]	0.17
[77]	10
[91]	0.06

In the first communication option, having a built-in CAN controller, the dSPACE DS1103 boards allow direct communication with an insignificant processing delay. For the second communication option, we configured the wireless adapters installed on Raspberry PI model 3 B+ boards to ensure wireless connectivity between the three inverters. The message with the two secondary control signals is read by the Raspberry PI from the dSPACE master controller through a serial connection; it is then encapsulated in a User Datagram Protocol (UDP) packet, and broadcast into the WiFi network. UDP is employed as a straightforward solution to one-shot communications without the need to establish a session with the end-points. Broadcast packets are listened to by the receiving controllers by means of similar wireless adapters.

The communication network effect on the secondary control loop, characterized by a proportional-integrative action, is usually modeled as a first-order delay element. As previously highlighted in the manuscript, the studies addressing the effect of communication delay on secondary control performance [26], [28], [37], [38], [42], [43], [77] point to a similar conclusion related to the practical necessity of developing a secondary control loop that allows a wide range of communication delays without loss of system's stability. However, there is little practical evidence on the real effect of different communication technologies on MG performance. As can be seen in Table 4, the maximum allowed communication delay for secondary control in MGs varies within a wide range. The MG employed in this paper accepts a communication delay of up to 2s (theoretical).

The end effect of communication upon secondary control will be assessed by criteria related to MG dynamic behavior. A communication delay may have various causes, such as high data traffic in the network, long path of data transmission requiring the packets to pass through multiple nodes, short-term loss of connection or re-transmissions in case of erroneous received packets. Another issue, mainly related to wireless communication, is the data dropouts.

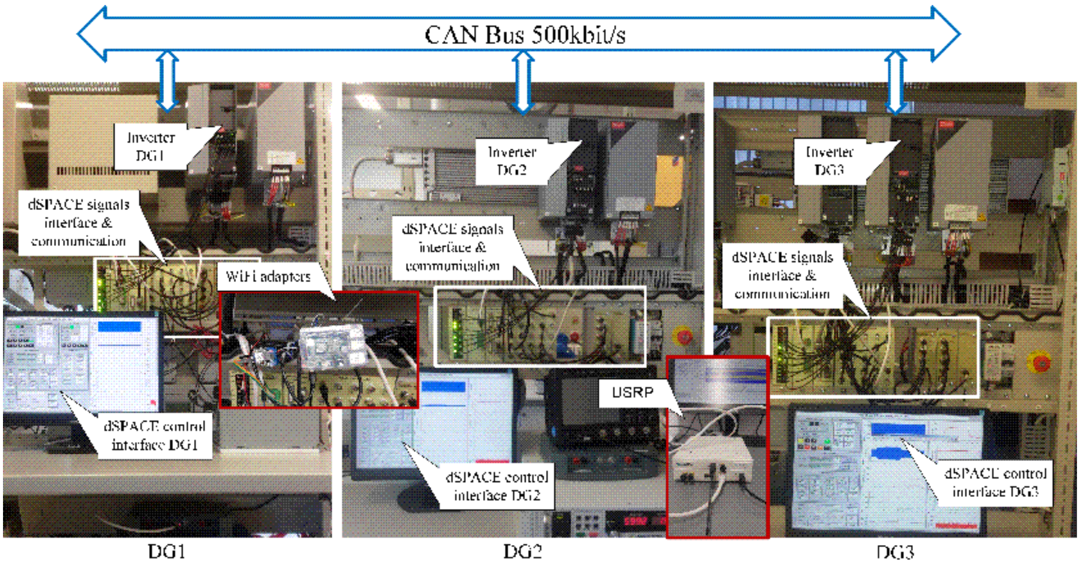

FIGURE 5. **Illustration of the MG laboratory employed in the experimental study.**

The analysis provided in this Section includes scenarios inspired by the challenges of real applications. Since wireless communication can more easily be disturbed by external sources, the experimental tests have been carried out with different perturbation levels. For this purpose, a National Instruments (NI) Universal Software Radio Peripheral (USRP) was used to generate interference in the WiFi network. Specifically, a NI USRP-2922 was used to generate interference uniformly within the channel used by the WiFi network in the 2.4 GHz frequency band. The level of interference was adjusted from zero to a level at which the WiFi network was almost completely disrupted and the three DGs were no longer able to communicate properly. From these experiments, the following cases were selected to support the analysis provided in this paper:

- Case 1: wired CAN;
- Case 2: WiFi w/o perturbation;
- Case 3: WiFi w/ continuous perturbation at a level where the communication performance deterioration becomes noticeable in the MG performance;
- Case 4: WiFi w/ continuous perturbation at a high level where the communication is almost completely disrupted;
- Case 5: WiFi w/ burst perturbation between the levels from Case 3 and Case 4.

In order to test the MG response in the cases above, a 4.5 kW resistive load was switched on and off at an interval of 7 s. The impact of communication performance on the MG performance was evaluated using quantitative criteria related to dynamic MG response. Since the load switching creates a change in the MG active power flow, the analysis focused on frequency behavior. Therefore, the following dynamic performance indicators for frequency response were considered:

- Relative maximum frequency deviation, expressed in (1);
- Integral of squared error of frequency, calculated as in (2), with $t_1 = 14$ s being the acquisition time.

$$\Delta f_{max}[\%] = \max\left(\left|\frac{f(t)}{50} - 1\right|\right) \cdot 100, \tag{1}$$

$$ISE_f = \int_0^{t_1} (f(t) - 50)^2 dt. \tag{2}$$

The performance of communication was evaluated by means of the following two parameters:

- Latency (or delay), expressed as the time interval required to pass a data packet from sender (DG1) to receivers (DG2, DG3), within the acquisition time;
- Packet loss, representing the number of packets failing to reach the destination within the acquisition time.

As shown in Fig. 6, the MG frequency response was directly influenced by the capability of the communication network to transmit the secondary control signals with an appropriate rate. A quantitative evaluation of the frequency response and communication performance is provided in Table 5. In the first two cases, with the wired and wireless communication fully operational, the MG frequency had a similar response. There was only a minor increase of the maximum frequency deviation in the case of WiFi communication because of the slightly higher data transmission latency, as expected.

With the WiFi signal perturbed at a medium level (case 3), the data packets were slightly more delayed and came at different rates. As a consequence, the secondary control tended to be more oscillatory and the MG frequency response was more visibly affected (i.e. the maximum frequency deviation increases by more than 0.5%). In the most severe scenario (case 4), because of the high level of wireless signal perturbation, the communication was almost completely lost (i.e., 99.5% of data packets are lost), and the insignificant number of packets that did arrive to their destinations were

TABLE 5. Indicators of the system's performance.

Experiment	Δf_{max} [%]	ISE_f [Hz^2s]	$Latency$ [1] [s]	$Pack.loss$ [2] [%]
Case 1	0.88	0.58	≈ 0	0
Case 2	0.94	0.62	0.09	0
Case 3	1.42	0.78	0.19	0
Case 4	1.69	4.38	– [3]	99.5
Case 5	1.05	0.73	0.48	10

[1] Average communication latency during experiment.
[2] Cumulative packet loss of both clients (DG2 and DG3)
[3] No meaningful data to calculate latency

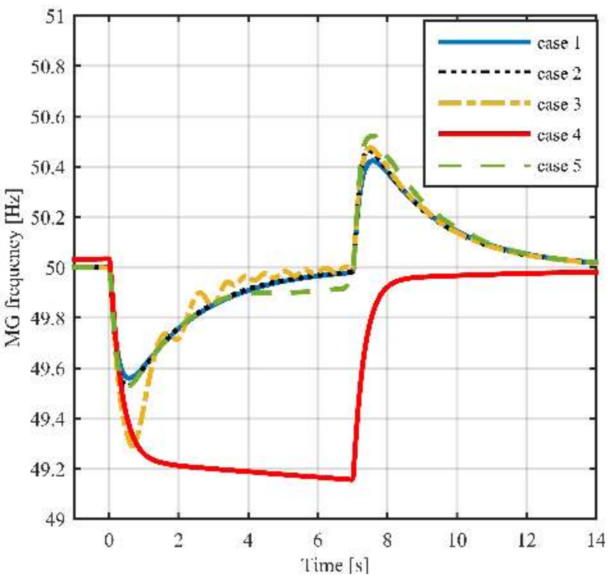

FIGURE 6. MG frequency response evaluated in different communication scenarios.

highly delayed. Under these conditions, the secondary controller could no longer restore the MG frequency, which remains at a level limited by the primary control.

The final case analyzed (case 5) shows that, in the short period the WiFi signal was perturbed (between $t \cong 3$ s - 6 s), the MG frequency restoration was stalled, while the secondary control resumed its action once the communication was reestablished. Therefore, we can conclude that, although the secondary control process may be significantly perturbed, microgrid stability is not affected by the deterioration of communication performance. This analysis reveals the importance of designing future secondary control solutions that are highly robust to communication failure such that the system's stability is not affected by commonplace instances of impairment or even complete loss of communication.

VI. OPEN RESEARCH CHALLENGES

Sustained by the need for a seamless transition of current power systems into the future smart grid, the developments in the field of MGs continue pushing the boundaries of technology in power electronics and control. With the progress of advanced control techniques a new technical challenge related to information exchange in MGs has emerged. As this paper has revealed, deploying a reliable communication infrastructure that satisfies the performance requirements of a modern MG is not an easy task. While most of the studies tackling the communication issue in MGs have focused on the impact latency (or delay) and packet losses have on MG performance, once the research takes into account wireless technologies, which allow easier expansion of communication infrastructure at lower costs, other security-related issues arise.

Among the three MG control layers shown in Fig. 2, the most demanding in terms of communication performance is the secondary control, which includes real-time mechanisms based on different architectures (e.g. centralized or distributed) to restore voltage and frequency in the MG. Therefore, a major challenge open for future research consists of safely deploying wireless communication technologies (including the emergent 5G cellular) for MG control. Concomitantly, research should focus on developing secondary control structures less vulnerable to communication disruptions related to technical malfunctions and cyber-security.

From our evaluation, WiFi can be seen as a communication technology suitable for MGs because capabilities such as scalability, monitoring, management, redundancy, and security can be easily included, at a low cost. Moreover, this technology can be used even without internet connection, as often occurs in rural areas. Although long-range WiFi applications have been reported, technical and regulatory issues need to be overcome in order to massify this technology in outdoor environments.

Networks that are 5G based are emerging as a reliable solution for communication in MGs; however, the advantages provided by this new technology are obvious for now only in the context of a multi-MG smart grid (as shown in Fig. 1). According to our evaluation, only in this case can the economic burden required by the 5G communication network be overcome by a conceptual new control of the smart grid based on the qualities of 5G communication networks. Furthermore, 5G comes with the advantage that distributed cloud services can be used so that some computational burden and services, mainly related to tertiary control, can be moved to the cloud. Therefore, deploying the new wireless communication technologies into the MG control layers and developing new conceptual control methods based on the qualities of these communication networks remain open issues for future research.

From our analysis, then, the following key aspects need to be tackled by future research in the field of MG communication:

- Developing smart control solutions that are more robust to communication degradation in MGs;
- Continuing the initiated efforts towards achieving full interoperability between various communication protocols and technologies, and enhancing communication reliability and security through redundancy;

- Developing failure-secure mechanisms integrated into the MG controllers to reduce the impact of communication malfunctioning and security issues.
- Establishing the value added with the integration of the emerging communication technologies (e.g., LPWAN and 5G cellular) in the MG control layers.

VII. CONCLUSION

The growth, development, and implementation of MGs have evolved during the last years from classical MG power networks into more advanced power and communication networks. As this paper has revealed, deploying a safe, reliable and adequate-performance communication solution for MGs represents a task with multiple technical challenges. In particular, the integration of wireless communications will bring scalable deployments at reduced costs, but will also require addressing greater communication impairments than in the wired solutions, as demonstrated by the experimental study presented in this paper. Therefore, choosing the appropriate communication technologies and standards, which should accordingly offer the required levels of reliability, security, and performance, represents a challenge in the near future when considering MG design.

Within the MG control hierarchy, three levels of control exist (primary, secondary, and tertiary), each having different requirements in terms of communication performance. The primary level is a time-critical mechanism that ensures instantaneous voltage and frequency control and, therefore, communication-less control methods, such as droop control, virtual synchronous generator control, are usually adopted. On the other hand, the tertiary level involves tasks related to MG energy management, hence non-critical data is transferred though communication network. It is in the secondary level where communications have a greater impact on MG control performance. Several secondary control approaches are found in the literature, which can be classified as centralized, distributed and mixed. The distributed control systems and/or mixed centralized and distributed control systems provide more reliable performance than pure centralized control [communication] systems. However, the secondary control level is most affected by the local MG communication network, where quasi real-time communication is required. The speed of the communication system directly affects the performance of secondary control; therefore, a trade-off between transitory response and bandwidth is usually encountered.

Data transmission requirements in terms of rate, delay (or latency), and reliability are established to comply with specific functions necessary to accomplish a proper operation. The control architecture, i.e. centralized or distributed, represents another feature of the MGs which is highly-dependent on the communication performance. While distributed control provides several advantages over a centralized scheme (e.g. higher reliability and robustness against unit failure), it may require more complex data transmission through communication lines.

Another important aspect is the communication network architecture and transmission media. For reliable, fast, secure, and real-time communication without data packet losses, fiber-optical communication systems would be the most adequate, but for economic reasons and the added costs and complications with later expansions in wide area networks, the use of wireless technologies seems to be an appropriate solution. The use of wireless technologies, however, generates a trade-off between communication delay and control performance in the MG, as the experimental analysis provided in this paper has shown. Furthermore, the importance of designing secondary control solutions that are highly robust when confronted with communication impairments or even complete loss of communication also needs to be considered in future research efforts.

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REFERENCES

[1] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. De Vicuña, and M. Castilla, ''Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization,'' *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 158–172, Jan. 2010.

[2] D. M. Laverty, D. J. Morrow, R. Best, and P. A. Crossley, ''Telecommunications for smart grid: Backhaul solutions for the distribution network,'' in *Proc. IEEE PES Gen. Meeting*, Jul. 2010, pp. 1–6.

[3] S. F. Bush, S. Goel, and G. Simard, ''IEEE vision for smart grid communications: 2030 and beyond roadmap,'' in *Proc. IEEE Vis. Smart Grid Commun., Beyond Roadmap*, Sep. 2013, pp. 1–19.

[4] R. Ma, H.-H. Chen, Y.-R. Huang, and W. Meng, ''Smart grid communication: Its challenges and opportunities,'' *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 36–46, Mar. 2013.

[5] M. Faheem, S. B. H. Shah, R. A. Butt, B. Raza, M. Anwar, M. W. Ashraf, M. A. Ngadi, and V. C. Gungor, ''Smart grid communication and information technologies in the perspective of industry 4.0: Opportunities and challenges,'' *Comput. Sci. Rev.*, vol. 30, pp. 1–30, Nov. 2018.

[6] E. Bullich-Massagué, F. Díaz-González, M. Aragüés-Peñalba, F. Girbau-Llistuella, P. Olivella-Rosell, and A. Sumper, ''Microgrid clustering architectures,'' *Appl. Energy*, vol. 212, pp. 340–361, Feb. 2018.

[7] T. L. Vandoorn, J. C. Vasquez, J. De Kooning, J. M. Guerrero, and L. Vandevelde, ''Microgrids: Hierarchical control and an overview of the control and reserve management strategies,'' *IEEE Ind. Electron. Mag.*, vol. 7, no. 4, pp. 42–55, Dec. 2013.

[8] J. Vasquez, J. Guerrero, J. Miret, M. Castilla, and L. Garcia de Vicuna, ''Hierarchical control of intelligent microgrids,'' *IEEE Ind. Electron. Mag.*, vol. 4, no. 4, pp. 23–29, Dec. 2010.

[9] A. Bidram and A. Davoudi, ''Hierarchical structure of microgrids control system,'' *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1963–1976, Dec. 2012.

[10] O. Palizban and K. Kauhaniemi, ''Hierarchical control structure in microgrids with distributed generation: Island and grid-connected mode,'' *Renew. Sustain. Energy Rev.*, vol. 44, pp. 797–813, Apr. 2015.

[11] A. M. Bouzid, J. M. Guerrero, A. Cheriti, M. Bouhamida, P. Sicard, and M. Benghanem, ''A survey on control of electric power distributed generation systems for microgrid applications,'' *Renew. Sustain. Energy Rev.*, vol. 44, pp. 751–766, Apr. 2015.

[12] H. Bevrani, T. Ise, and Y. Miura, ''Virtual synchronous generators: A survey and new perspectives,'' *Int. J. Electr. Power Energy Syst.*, vol. 54, pp. 244–254, Jan. 2014.

[13] *IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems With Electric Power Systems*, IEEE Standard 1547.4-2011, Jul. 2011, pp. 1–54.

[14] S. Safdar, B. Hamdaoui, E. Cotilla-Sanchez, and M. Guizani, ''A survey on communication infrastructure for micro-grids,'' in *Proc. 9th Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Jul. 2013, pp. 545–550.

[15] V. S. Bindhu and D. M. Mary Synthia Regis Prabha, "A survey on control and communication of smart micro grid," *Indian J. Sci. Technol.*, vol. 8, no. 25, pp. 1–6, Oct. 2015.

[16] P. D. Chavan and R. J. Devi, "Survey of communication system for DG's and microgrid in electrical power grid," *Int. Res. J. Eng. Technol.*, vol. 3, no. 7, pp. 1155–1164, 2016.

[17] A. Bani-Ahmed, L. Weber, A. Nasiri, and H. Hosseini, "Microgrid communications: State of the art and future trends," in *Proc. Int. Conf. Renew. Energy Res. Appl. (ICRERA)*, Oct. 2014, pp. 780–785.

[18] J. Liu, Y. Miura, and T. Ise, "Comparison of dynamic characteristics between virtual synchronous generator and droop control in inverter-based distributed generators," *IEEE Trans. Power Electron.*, vol. 31, no. 5, pp. 3600–3611, May 2016.

[19] N. Hatziargyriou, *Microgrids: Architectures and Control*. Hoboken, NJ, USA: Wiley, 2014.

[20] H. Han, X. Hou, J. Yang, J. Wu, M. Su, and J. M. Guerrero, "Review of power sharing control strategies for islanding operation of AC microgrids," *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 200–215, Jan. 2016.

[21] A. Mortezaei, M. Simoes, M. Savaghebi, J. Guerrero, and A. A. Durra, "Cooperative control of multi-master-slave islanded microgrid with power quality enhancement based on conservative power theory," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2017, pp. 2964–2975.

[22] S. Liu, X. Wang, and P. X. Liu, "Impact of communication delays on secondary frequency control in an islanded microgrid," *IEEE Trans. Ind. Electron.*, vol. 62, no. 4, pp. 2021–2031, Apr. 2015.

[23] A. M. Roslan, K. H. Ahmed, S. J. Finney, and B. W. Williams, "Improved instantaneous average current-sharing control scheme for parallel-connected inverter considering line impedance impact in micro-grid networks," *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 702–716, Mar. 2011.

[24] N. L. Diaz, J. C. Vasquez, and J. M. Guerrero, "A communication-less distributed control architecture for islanded microgrids with renewable generation and storage," *IEEE Trans. Power Electron.*, vol. 33, no. 3, pp. 1922–1939, Mar. 2018.

[25] E. Serban and H. Serban, "A control strategy for a distributed power generation microgrid application with voltage-and current-controlled source converter," *IEEE Trans. Power Electron.*, vol. 25, no. 12, pp. 2981–2992, Dec. 2010.

[26] Y. Khayat, J. M. Guerrero, H. Bevrani, Q. Shafiee, R. Heydari, M. Naderi, T. Dragicevic, J. W. Simpson-Porco, F. Dorfler, M. Fathi, and F. Blaabjerg, "On the secondary control architectures of AC microgrids: An overview," *IEEE Trans. Power Electron.*, vol. 35, no. 6, pp. 6482–6500, Jun. 2020.

[27] J. M. Rey, P. Marti, M. Velasco, J. Miret, and M. Castilla, "Secondary switched control with no communications for islanded microgrids," *IEEE Trans. Ind. Electron.*, vol. 64, no. 11, pp. 8534–8545, Nov. 2017.

[28] Y. Khayat, M. Naderi, Q. Shafiee, Y. Batmani, M. Fathi, J. M. Guerrero, and H. Bevrani, "Decentralized optimal frequency control in autonomous microgrids," *IEEE Trans. Power Syst.*, vol. 34, no. 3, pp. 2345–2353, May 2019.

[29] M. Castilla, A. Camacho, P. Marti, M. Velasco, and M. M. Ghahderijani, "Impact of clock drifts on communication-free secondary control schemes for inverter-based islanded microgrids," *IEEE Trans. Ind. Electron.*, vol. 65, no. 6, pp. 4739–4749, Jun. 2018.

[30] P. Marti, J. Torres-Martinez, C. X. Rosero, M. Velasco, J. Miret, and M. Castilla, "Analysis of the effect of clock drifts on frequency regulation and power sharing in inverter-based islanded microgrids," *IEEE Trans. Power Electron.*, vol. 33, no. 12, pp. 10363–10379, Dec. 2018.

[31] C. Cho, J.-H. Jeon, J.-Y. Kim, S. Kwon, K. Park, and S. Kim, "Active synchronizing control of a microgrid," *IEEE Trans. Power Electron.*, vol. 26, no. 12, pp. 3707–3719, Dec. 2011.

[32] I. Ziouani, D. Boukhetala, A.-M. Darcherif, B. Amghar, and I. El Abbassi, "Hierarchical control for flexible microgrid based on three-phase voltage source inverters operated in parallel," *Int. J. Electr. Power Energy Syst.*, vol. 95, pp. 188–201, Feb. 2018.

[33] F. Tang, J. M. Guerrero, J. C. Vasquez, D. Wu, and L. Meng, "Distributed active synchronization strategy for microgrid seamless reconnection to the grid under unbalance and harmonic distortion," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2757–2769, Nov. 2015.

[34] J. W. Simpson-Porco, Q. Shafiee, F. Dorfler, J. C. Vasquez, J. M. Guerrero, and F. Bullo, "Secondary frequency and voltage control of islanded microgrids via distributed averaging," *IEEE Trans. Ind. Electron.*, vol. 62, no. 11, pp. 7025–7038, Nov. 2015.

[35] Y. Sun, C. Zhong, X. Hou, J. Yang, H. Han, and J. M. Guerrero, "Distributed cooperative synchronization strategy for multi-bus microgrids," *Int. J. Electr. Power Energy Syst.*, vol. 86, pp. 18–28, Mar. 2017.

[36] Y. Gao and Q. Ai, "A distributed coordinated economic droop control scheme for islanded AC microgrid considering communication system," *Electr. Power Syst. Res.*, vol. 160, pp. 109–118, Jul. 2018.

[37] J. Llanos, D. E. Olivares, J. W. Simpson-Porco, M. Kazerani, and D. Saez, "A novel distributed control strategy for optimal dispatch of isolated microgrids considering congestion," *IEEE Trans. Smart Grid*, vol. 10, no. 6, pp. 6595–6606, Nov. 2019.

[38] J. S. Gomez, D. Saez, J. W. Simpson-Porco, and R. Cardenas, "Distributed predictive control for frequency and voltage regulation in microgrids," *IEEE Trans. Smart Grid*, vol. 11, no. 2, pp. 1319–1329, Mar. 2020.

[39] A. Micallef, M. Apap, C. Spiteri-Staines, and J. M. Guerrero, "Single-phase microgrid with seamless transition capabilities between modes of operation," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2736–2745, Nov. 2015.

[40] C.-L. Chen, Y. Wang, J.-S. Lai, Y.-S. Lee, and D. Martin, "Design of parallel inverters for smooth mode transfer microgrid applications," *IEEE Trans. Power Electron.*, vol. 25, no. 1, pp. 6–15, Jan. 2010.

[41] Y. A.-R.-I. Mohamed and A. A. Radwan, "Hierarchical control system for robust microgrid operation and seamless mode transfer in active distribution systems," *IEEE Trans. Smart Grid*, vol. 2, no. 2, pp. 352–362, Jun. 2011.

[42] I. Serban, "A control strategy for microgrids: Seamless transfer based on a leading inverter with supercapacitor energy storage system," *Appl. Energy*, vol. 221, pp. 490–507, Jul. 2018.

[43] G. Lou, W. Gu, J. Wang, W. Sheng, and L. Sun, "Optimal design for distributed secondary voltage control in islanded microgrids: Communication topology and controller," *IEEE Trans. Power Syst.*, vol. 34, no. 2, pp. 968–981, Mar. 2019.

[44] Q. Shafiee, J. M. Guerrero, and J. C. Vasquez, "Distributed secondary control for islanded Microgrids—A novel approach," *IEEE Trans. Power Electron.*, vol. 29, no. 2, pp. 1018–1031, Feb. 2014.

[45] W. Meng, X. Wang, and S. Liu, "Distributed load sharing of an inverter-based microgrid with reduced communication," *IEEE Trans. Smart Grid*, vol. 9, no. 2, pp. 1354–1364, Mar. 2018.

[46] M. S. Golsorkhi, D. J. Hill, and H. R. Karshenas, "Distributed voltage control and power management of networked microgrids," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 6, no. 4, pp. 1892–1902, Dec. 2018.

[47] S. Marzal, R. Salas, R. González-Medina, G. Garcerá, and E. Figueres, "Current challenges and future trends in the field of communication architectures for microgrids," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 3610–3622, Feb. 2018.

[48] M. A. Setiawan, F. Shahnia, S. Rajakaruna, and A. Ghosh, "ZigBee-based communication system for data transfer within future microgrids," *IEEE Trans. Smart Grid*, vol. 6, no. 5, pp. 2343–2355, Sep. 2015.

[49] H. Zou, S. Mao, Y. Wang, F. Zhang, X. Chen, and L. Cheng, "A survey of energy management in interconnected multi-microgrids," *IEEE Access*, vol. 7, pp. 72158–72169, 2019.

[50] N. W. A. Lidula and A. D. Rajapakse, "Voltage balancing and synchronization of microgrids with highly unbalanced loads," *Renew. Sustain. Energy Rev.*, vol. 31, pp. 907–920, Mar. 2014.

[51] J. Giraldo, E. Mojica-Nava, and N. Quijano, "Synchronization of isolated microgrids with a communication infrastructure using energy storage systems," *Int. J. Electr. Power Energy Syst.*, vol. 63, pp. 71–82, Dec. 2014.

[52] A. Vaccaro, V. Loia, G. Formato, P. Wall, and V. Terzija, "A self-organizing architecture for decentralized smart microgrids synchronization, control, and monitoring," *IEEE Trans Ind. Informat.*, vol. 11, no. 1, pp. 289–298, Feb. 2015.

[53] M. Z. Gunduz and R. Das, "Cyber-security on smart grid: Threats and potential solutions," *Comput. Netw.*, vol. 169, Mar. 2020, Art. no. 107094.

[54] S. Mehrdad, S. Mousavian, G. Madraki, and Y. Dvorkin, "Cyber-physical resilience of electrical power systems against malicious attacks: A review," *Current Sustain./Renew. Energy Rep.*, vol. 5, no. 1, pp. 14–22, Jan. 2018.

[55] M. H. Wen, K.-C. Leung, V. O. Li, X. He, and C.-C. J. Kuo, "A survey on smart grid communication system," *APSIPA Trans. Signal Inf. Process.*, vol. 4, pp. 1–20, Aug. 2015.

[56] *IEEE Standard for the Specification of Microgrid Controllers*, IEEE Standard 2030.7-2017, IEEE Power and Energy Society, 2017, pp. 1–42.

[57] I. Ali and S. Hussain, "Communication design for energy management automation in microgrid," *IEEE Trans. Smart Grid*, to be published.

[58] W. Wang, Y. Xu, and M. Khanna, ‘‘A survey on the communication architectures in smart grid,’’ *Comput. Netw.*, vol. 55, no. 15, pp. 3604–3629, Oct. 2011.
[59] T. T. Mai, A. N. M. M. Haque, T. Vo, P. H. Nguyen, and M. C. Pham, ‘‘Development of ICT infrastructure for physical LV microgrids,’’ in *Proc. IEEE Int. Conf. Environ. Electr. Eng. IEEE Ind. Commercial Power Syst. Eur. (EEEIC/I&CPS Eur.)*, Jun. 2018, pp. 1–6.
[60] R. H. Khan and J. Y. Khan, ‘‘A comprehensive review of the application characteristics and traffic requirements of a smart grid communications network,’’ *Comput. Netw.*, vol. 57, no. 3, pp. 825–845, Feb. 2013.
[61] H. Li, A. Dimitrovski, J. B. Song, Z. Han, and L. Qian, ‘‘Communication infrastructure design in cyber physical systems with applications in smart grids: A hybrid system framework,’’ *IEEE Commun. Surveys Tutr.*, vol. 16, no. 3, pp. 1689–1708, 3rd Quart., 2014.
[62] T. Dragi ević, P. Siano, and S. R. Prabaharan, ‘‘Future generation 5G wireless networks for smart grid: A comprehensive review,’’ *Energies*, vol. 12, no. 11, p. 2140, Jun. 2019.
[63] G. Bag, L. Thrybom, and P. Hovila, ‘‘Challenges and opportunities of 5G in power grids,’’ *CIRED-Open Access Proc. J.*, vol. 2017, no. 1, pp. 2145–2148, Oct. 2017.
[64] B. Arbab-Zavar, E. Palacios-Garcia, J. Vasquez, and J. Guerrero, ‘‘Smart inverters for microgrid applications: A review,’’ *Energies*, vol. 12, no. 5, p. 840, Mar. 2019.
[65] K. Monteiro, M. Marot, and H. Ibn-Khedher, ‘‘Review on microgrid communications solutions: A named data networking–fog approach,’’ in *Proc. 16th Annu. Medit. Ad Hoc Netw. Workshop (Med-Hoc-Net)*, Jun. 2017, pp. 1–8.
[66] W. Zhou, Z. Tong, Z. Y. Dong, and Y. Wang, ‘‘LoRa-hybrid: A LoRaWAN based multihop solution for regional microgrid,’’ in *Proc. IEEE 4th Int. Conf. Comput. Commun. Syst. (ICCCS)*, Feb. 2019, pp. 650–654.
[67] L. K. A. Terashmila, T. Iqbal, and G. Mann, ‘‘A comparison of low cost wireless communication methods for remote control of grid-tied converters,’’ in *Proc. IEEE 30th Can. Conf. Electr. Comput. Eng. (CCECE)*, Apr. 2017, pp. 1–4.
[68] G. Fadda, M. Fadda, E. Ghiani, and V. Pilloni, ‘‘Communications and Internet of Things for microgrids, smart buildings, and homes,’’ in *Distributed Energy Resources in Microgrids*. Amsterdam, The Netherlands: Elsevier, 2019, pp. 243–273.
[69] A. Mahmood, N. Javaid, and S. Razzaq, ‘‘A review of wireless communications for smart grid,’’ *Renew. Sustain. Energy Rev.*, vol. 41, pp. 248–260, Jan. 2015.
[70] C. Kalalas, L. Thrybom, and J. Alonso-Zarate, ‘‘Cellular communications for smart grid neighborhood area networks: A survey,’’ *IEEE Access*, vol. 4, pp. 1469–1493, 2016.
[71] S. Galli, A. Scaglione, and Z. Wang, ‘‘For the grid and through the grid: The role of power line communications in the smart grid,’’ *Proc. IEEE*, vol. 99, no. 6, pp. 998–1027, Jun. 2011.
[72] A. Varghese, D. Tandur, and A. Ray, ‘‘Suitability of WiFi based communication devices in low power industrial applications,’’ in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Mar. 2017, pp. 1307–1312.
[73] K. Ab-Hamid, C. E. Tan, and S. P. Lau, ‘‘Self-sustainable energy efficient long range WiFi network for rural communities,’’ in *Proc. IEEE GLOBECOM Workshops (GC Wkshps)*, Dec. 2011, pp. 1050–1055.
[74] *IMT Vision–Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond*, document ITU-R M.2083, 2015.
[75] O. Starynets, ‘‘Communication in microgrids and virtual power plants,’’ M.S. thesis, Dept. Elect. Eng., UiT Norges Arktiske Univ., Tromsø, Norway, 2016.
[76] G. Stanciulescu, H. Farhangi, A. Palizban, and N. Stanchev, ‘‘Communication technologies for BCIT smart microgrid,’’ in *Proc. IEEE PES Innov. Smart Grid Technol. (ISGT)*, Jan. 2012, pp. 1–7.
[77] Q. Shafiee, C. Stefanovic, T. Dragicevic, P. Popovski, J. C. Vasquez, and J. M. Guerrero, ‘‘Robust networked control scheme for distributed secondary control of islanded microgrids,’’ *IEEE Trans. Ind. Electron.*, vol. 61, no. 10, pp. 5363–5374, Oct. 2014.
[78] S. Ci, J. Qian, D. Wu, and A. Keyhani, ‘‘Impact of wireless communication delay on load sharing among distributed generation systems through smart microgrids,’’ *IEEE Wireless Commun.*, vol. 19, no. 3, pp. 24–29, Jun. 2012.
[79] B. Chaudhuri, R. Majumder, and B. C. Pal, ‘‘Wide-area measurement-based stabilizing control of power system considering signal transmission delay,’’ *IEEE Trans. Power Syst.*, vol. 19, no. 4, pp. 1971–1979, Nov. 2004.
[80] M. M. Rana, ‘‘Least mean square fourth based microgrid state estimation algorithm using the Internet of Things technology,’’ *PLoS ONE*, vol. 12, no. 5, May 2017, Art. no. e0176099.
[81] M. M. Rana, L. Li, and S. W. Su, ‘‘Distributed state estimation of smart grids with packet losses,’’ *Asian J. Control*, vol. 19, no. 4, pp. 1306–1315, Jun. 2017.
[82] E. Lazar, R. Etz, D. Petreus, T. Patarau, and I. Ciocan, ‘‘SCADA development for an islanded microgrid,’’ in *Proc. IEEE 21st Int. Symp. for Des. Technol. Electron. Packag. (SIITME)*, Oct. 2015, pp. 147–150.
[83] X. Zhaoxia, G. Zhijun, J. M. Guerrero, and F. Hongwei, ‘‘SCADA system for islanded DC microgrids,’’ in *Proc. IECON - 43rd Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2017, pp. 2669–2674.
[84] E.-K. Lee, W. Shi, R. Gadh, and W. Kim, ‘‘Design and implementation of a microgrid energy management system,’’ *Sustainability*, vol. 8, no. 11, p. 1143, Nov. 2016.
[85] L. Zhang, J. Xiao, P. Wang, and X. Pan, ‘‘Design and implementation of communication network for modular microgrid based power park,’’ in *Proc. IEEE Innov. Smart Grid Technol.-Asia (ISGT-Asia)*, Nov. 2016, pp. 160–165.
[86] F. M. Sallabi, A. M. Gaouda, A. H. El-Hag, and M. M. A. Salama, ‘‘Evaluation of ZigBee wireless sensor networks under high power disturbances,’’ *IEEE Trans. Power Del.*, vol. 29, no. 1, pp. 13–20, Feb. 2014.
[87] M. Buevich, X. Zhang, O. Shih, D. Schnitzer, T. Escalada, A. Jacquiau-Chamski, J. Thacker, and A. Rowe, ‘‘Microgrid losses: When the whole is greater than the sum of its parts,’’ in *Proc. ACM/IEEE 7th Int. Conf. Cyber-Phys. Syst. (ICCPS)*, Apr. 2016, p. 46.
[88] E. Habib and G. Khaled, ‘‘ZigBee investigation within smart micro grid,’’ *IJIREEICE*, vol. 4, no. 3, pp. 212–214, Mar. 2016.
[89] H. Elkhorchani and K. Grayaa, ‘‘Smart micro grid power with wireless communication architecture,’’ in *Proc. Int. Conf. Electr. Sci. Technol. Maghreb (CISTEM)*, Nov. 2014, pp. 1–10.
[90] C. Ahumada, R. Cardenas, D. Saez, and J. M. Guerrero, ‘‘Secondary control strategies for frequency restoration in islanded microgrids with consideration of communication delays,’’ *IEEE Trans. Smart Grid*, vol. 7, no. 3, pp. 1430–1441, May 2016.
[91] G. Lou, W. Gu, Y. Xu, W. Jin, and X. Du, ‘‘Stability robustness for secondary voltage control in autonomous microgrids with consideration of communication delays,’’ *IEEE Trans. Power Syst.*, vol. 33, no. 4, pp. 4164–4178, Jul. 2018.

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