Considerations on Communication Infrastructures for Cooperative Operation of Smart Inverters

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***Abstract*—The presence of distributed generation systems spread over low-voltage electrical networks is boosting the development of control methodologies aiming at coordinating and cooperatively managing the existing smart inverters. Although low-bandwidth data transmission links are constantly described to be required for a considerable number of centralized and decentralized control methodologies, there is a gap in literature concerning the plain understanding of the features of the related communication protocols available for such application. Thus, this paper brings considerations on some of the most relevant communication protocols that can be applied to the cooperative control of multiple smart inverters, taking into account the recent updates on interoperability requirements recommended by the IEEE 1547-2018 standard. The communication infrastructure, topology and features of a low-bandwidth data transmission link are discussed in this paper focusing on the SunSpec, DNP3 and SEP2 protocols. Yet, some critical comments are made regarding the practical interoperability of commercial inverters, also bordering cyber security matters.**

Keywords—Communication protocol, cooperative control, IEEE 1547 standard, microgrid, interoperability, smart inverter.

I. Introduction

Since the past decades, the dense presence of distributed energy sources (DERs) in low-voltage distribution systems has been playing a key role in the decentralization of energy generation, allowing renewables to be inserted into the new digitized paradigm of electrical networks [1], which brings the Smart Grid (SG) concept to reality. As electrical grids move towards SG implementation, the adoption of intelligent mechanisms and provision of higher interactivity among electronic devices is inevitable [2]. Consequently, the employment of communication technologies within electrical networks, especially in dynamic and more interactive systems such as microgrids (MGs) [3], is being required for many related applications [4].

A particular application of communications, which is gaining significant attention in literature, is related to power electronic interfaces existing within DERs, in order to enable their cooperative operation. By driving smart inverters under an integrated approach, their provision of ancillary services can be coordinated to enhance the overall performance of MGs, especially by enabling power/current sharing and compensation functionalities such as reactive, unbalance and harmonic compensation [6]. Hence, several methodologies for cooperative operation of inverters, which are generally based on centralized or decentralized control approaches [7], are being proposed to provide integration of DERs [8]-[10].

Regardless of their control architecture, most methods for cooperative steering of smart inverters rely on low-bandwidth data transmission links to exchange information among agents, even though communication may not be required for the overall operation and stability maintenance of the MG. By doing so, local information can be exchanged with neighbors (e.g., as done by consensual approaches [11]) or with a central management system/controller (e.g., as done by centralized control [10], [12]). Therefore, through communication means, the cooperation of agents in MGs can be achieved accounting for the status of several nodes and striving for enhancing the overall performance of the electrical system.

Nonetheless, although a significant amount of research has been done [6]-[12] aiming at developing cooperative control methodologies which take advantage of low-bandwidth data transmission links, there is a gap in literature in regard to the description of such communication infrastructure and the related protocols that are available for the fulfillment of this particular purpose. To the best knowledge of the authors, most of previous works related to SGs focus, majorly, on information and communication technologies (ICTs) required for applications in metering (AMI) [13] and data exchange in the utility level [14]. Yet, when addressing communication in MGs [3,4], focus is seldom given to the application of smart inverters. Consequently, literature lacks discussions about communication infrastructures and protocols embedded in smart inverters for cooperative operation. Since recent updates on the IEEE 1547 – 2018 standard [15] consider such ICT matters for the compliance of smart inverters, it is of importance to discuss the requirements of the interoperability protocols for cooperative operation and networked control [16], laying the groundwork of this study.

Thus, this paper has the main goal of discussing the communication protocols highlighted within the IEEE 1547 – 2018, since they are the likely candidates to be implemented in real applications of cooperation among inverters. The paper is organized as follows. Firstly, in Section II, cooperative control is defined and a brief explanation is presented to highlight the communication architectures that fall within the scope of analysis. Later, an overview of the three protocols comprised within [15] (i.e., SunSpec, DNP3, and SEP2) is presented in Section III. Such discussion aims at showing their technical aspects and their applicability to different approaches of cooperative control. At last, a brief discussion

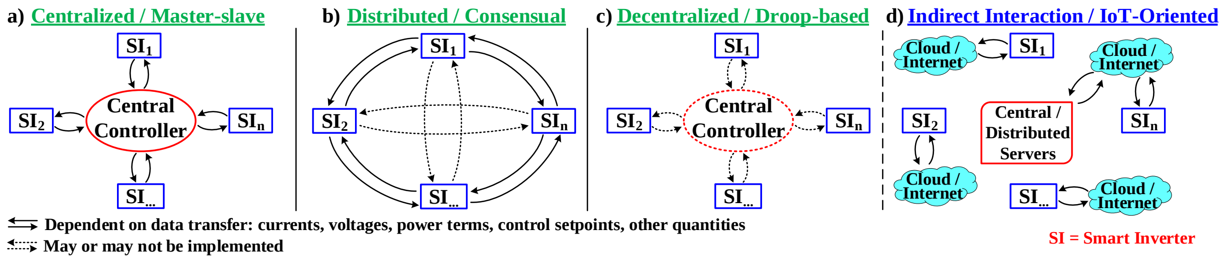

Fig. 1. Principle of operation of cooperative control strategies on which communication technologies are implemented to control "*n*" smart inverters.

oriented to communications is included in Section IV, concerning cyber security and the practical interoperability of commercial inverters.

II. Cooperative Control Strategies and Their use of Data Transmission Links

The principle of coordinated operation of smart inverters consists on steering them toward a common goal that, in general, corresponds to extracting the maximum power from the MG, additionally offering support to the grid under abnormal conditions and improving power quality. Depending on how such inverters are driven, different control strategies are required [5]-[12], and their cooperative operation is usually designed to follow a centralized, distributed or decentralized architecture, as summarized in Fig. 1. Cooperation through indirect methods, as shown in Fig. 1(d), is essentially based on one of the three previous designs, being later discussed. The most significant contrast among those architectures concerns how communication infrastructures are implemented, or if they are not used at all. Apart from that, cooperation of inverters is formulated based on exchanging information among agents (e.g., voltages, currents, power, control setpoints, so forth).

Regarding the communication framework, cooperative operation can be split into two main approaches that focus on the centralization or decentralization of the related data processing and consequently supervised control algorithms [6]-[8], as depicted in Fig. 2. For this first classification, communication is basically required to allow local agents (i.e., inverters) to exchange information with a central controller (CC), demanding control setpoints to steer their operations as a feedback from this interaction [10,12,17]. Moreover, the CC is mostly considered as a master unit, whereas the inverters are driven as slave agents [10]. This occurs based on point-to-point (P2P) low-bandwidth data transmission [18], which is a basic communication method characterized by punctual interactions of the CC (i.e., server) with each of all other distributed inverters (i.e., clients). It is highlighted that P2P communication differs from peer-to-peer networking. The latter does not require a central server for data transmission among agents, allowing each communicating unit to operate both as a client and a server [18].

Other strategies of cooperative control avoid the extensive use of P2P communication to minimize latency, since significant time is expended if a considerable number of inverters have to communicate with the CC sequentially. As a consequence, communication alternatives, such as additionally allowing the CC to broadcast generalized operational references as control feedback to all inverters, are proposed on some approaches [10,12,19]. On the other hand, another possible communication approach is the use of the point-to-multipoint (PMP) technology [20], which is characterized by the centralization of the data processing in the CC through a shared network. In such way, all inverters

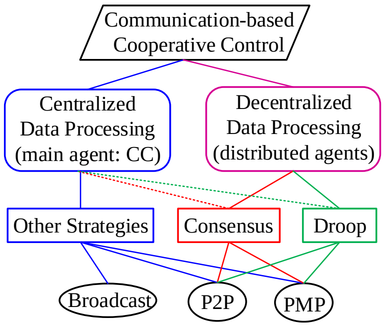

Fig. 2. Basic use of communication technologies for cooperative control.

have concomitant access to the same communication link carrying the operational control references. Briefly, by relying on communication with a central agent as a fundamental part of the overall coordinated operation of inverters, the strategy can be defined as centralized.

For the second approach (i.e., decentralized strategies), they are mostly based on droop control [8,9,21], which allows inverters to operate in parallel, not requiring an immediate communication link for the overall operation of the MG. However, several droop-based strategies present limitations in regard to, for instance, balancing the trade-off between accurate power sharing and deviations of frequency and/or voltages [22]. Therefore, alternative droop-based methods take advantage of communication links to implement control loops in the secondary and/or tertiary hierarchical layers to overcome such limitations [16], [21]. Note that, in this work, the definition of decentralized control strategy lies on the independence of communication links to perform basic cooperative control functionalities, such as active and reactive power sharing. Communication might be required to extend few functionalities of the above-mentioned decentralized methods by interacting with a CC, such as done in [17]; or yet, for inverters to exchange data among themselves, aiming at optimizing the overall operation of the MG. Thus, an infrastructure based on P2P or PMP communication may be used in such cases. Also, data exchange among inverters can occur based on novel methods of indirect interaction among agents (i.e., internet of things (IoT)-oriented), such as through the access to cloud servers [23] or by communicating using the concept of Energy Internet [24], as seen in Fig. 1(d). Note that such indirect concepts may be characterized as centralized, distributed or decentralized depending on how inverters interact with cloud/internet servers.

Finally, some consensus-based control methods [11], [25], lie in between centralized and decentralized operation due to the means required for the consensual convergence among inverters. Such strategies are decentralized since they do not rely on a centralized controller to perform local control of inverters, but they concomitantly depend on low latency communication channels to perform cooperative control. Usually, communication is simply set up for the consensus algorithm by just having distributed agents interacting with a few of their neighbors (i.e., adjacent inverters) through P2P, PMP or peer-to-peer data links.

Among all the aforementioned cooperative control strategies, there is a common agreement in relation to the requirement and use of the ICT infrastructure. Since inverters within MGs are usually distant from each other, or from the CC, the control strategy ought to stand operation following the use of low-bandwidth communication channels. Then, by low-bandwidth communication, it is meant a transmission mean with a low data transfer speed (i.e., up to a few hundreds of Kbps) between the communicating entities [18]. This holds independently of the physical layer employed for the exchange of data among agents (e.g., wireless, optical fiber, Ethernet). The consequence of this is that, if a strategy, either centralized or decentralized, requires an excessive amount of data to be transferred among agents, it may become unfeasible for real life applications. Such lack of feasibility may particularly occur due to the inherent delays and data transmission latency existing for all mentioned communication technologies [20]. In addition, although vaguely described in research literature, the mentioned low bit-rate communication interface embedded on inverters has to comply with interoperability features recently incorporated within standards, such as the IEEE 1547-2018 [15].

As a final remark, most of the previous works [6]-[14], superficially describe the communication link as a low-bandwidth channel and do not specify which of the three protocols proposed in [15] (i.e., SunSpec, DNP3, SEP2) should be used according to the type of communication required by each control layer of the method. Thus, the next section describes the features of each of these three protocols and initiates some discussion on their employment on different layers of application focusing on cooperative operation of inverters.

III. Communication Infrastructure and Protocols for Cooperative Smart Inverters

The recent updates comprised within the IEEE 1547-2018 focus on the interconnection and interoperability related to grid-connected inverters, particularly on their interaction among themselves and with other devices. The most significant changes on this regulation brings to reality the concept of smart inverters, which occurs through the provision of ancillary services, now recommending such converters to ride through abnormal voltage/frequency conditions, actively regulate voltage by adjusting reactive power, and many others [15]. Inverters must also comprise a communication interface. Thus, from the IEEE 1547-2018 recommendation that DERs must perform grid-support functions based on local measurements, while also comprising interoperability interfaces, the distributed generation sector steps forward to likely consider communication-based services, as expected for the ideal SG future [26]. Such communication-based functions enable more controllable and accurate power regulation in MGs, which in turns contributes to increase the system hosting capacity [26].

Particularly focusing on communication features, for any of the three protocols (i.e., SunSpec, DNP3 and SEP2), inverters must be able to communicate with external agents (e.g., other inverters, the CC, or metering devices) through the exchange of information under a certain infrastructure of data packet format as depicted in Fig. 3. Note that the following structure is independent on the data transmission technology

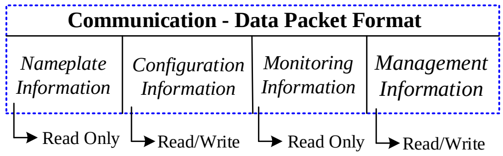

Fig. 3. Data packet configuration proposed in [15].

used (i.e., P2P, PMP, broadcast) and should be adequately considered on protocol level. Such communication should contain data classified within one of the four following categories, which are: nameplate, configuration data, monitoring measurement, and management information. This means that, upon the beginning of a new communication interaction between two agents, a data packet must be gathered by each inverter being grouped based on the following information:

- *Nameplate Information:* This piece of data presents a read-only feature, and consists of built-in information of the device. It comprises commercial information about the inverter, such as its model, manufacturer, serial number, as well as technical data given by its nominal and maximum active, reactive and apparent powers, its AC voltage ratings, along with many other defined inside [15]. This category presents read-only data, which allows the written information to be used, for instance, by a centralized controller for the calculation of operational setpoints as used in [10,12,19]. Nevertheless, this field of the data packet cannot be used for writing purposes. From this piece of the communication infrastructure it is also possible to interpret different types of devices exchanging data since, for example, data headers identify if the agent is an inverter (i.e., presenting ID = 1XX), a storage system (i.e., ID = 8XX), or many others [27]. Such feature may be used to facilitate implementation of control algorithms for cooperative strategies that require prior knowledge of the communication agents;
- *Configuration Information*: This category allows to modify the settings of the actual operational capacities of the inverter, which are by default based on the values presented in the nameplate information. This means that if, in any case, the MG operator intends to change the features of the converter by limiting its nominal ratings, it can be done by writing different data to this section of the communication packet. As consequence, by detecting nominal ratings different from the ones previously existing in the nameplate, the inverter must adjust its operation. This feature might be interesting while considering a coordinated operation in order to limit the output of inverters that are placed in critical nodes where resonances or other power quality issues may be triggered. In strategies on which specific quantities (i.e., beyond the basic ones already comprised within [15]) need be transmitted among the participating agents, such as values of peak currents [19], calculations of harmonic powers [8], etc), such information can be inserted in specific fields on this section of the data packet being exchanged;
- *Monitoring Information*: This section of the data packet mainly comprises the latest measurements performed by the inverter, not being accessible for writing data. In general, such information consists of active and reactive power, voltage and frequency, the state of charge of the possible energy storage system, and a few other quantities for supervision purposes

[15]. Of course, the data transmitted in this part of the packet present the basic electrical quantities required to be read for most of the cooperative control strategies that take advantage of communication [6]-[12];

- *Management Information*: Finally, the last category allows to read and write some functional and mode settings of the inverter. Here, functionalities such as constant power factor mode, active/reactive power curve points, frequency droop parameters, and many others can be adjusted to steer the inverter to operate as desired. Therefore, cooperative strategies based in droop control like [9,16,21] can, for instance, directly act on writing control setpoints on this portion of the communication packet.

The most beneficial reason for adopting inverters compliant with the IEEE 1547-2018 on cooperative control strategies is given by this basic standardization on the format of data packets being exchanged during communications. By following similar patterns of data structure, interpreting the transmitted information is facilitated. Thus, the SunSpec, DNP3 and SEP2 communication protocols are presented in the following to demonstrate their features and applicability to the distributed operation of inverters.

A. SunSpec Modbus Protocol

The SunSpec protocol was developed by the SunSpec Alliance, which incorporates manufacturers, technology developers and commercial providers, aiming at specifying an information and communication model focused on the interoperability of inverters and other devices comprised within the scope of SGs [27], [28]. Thus, it can be upfront mentioned that the SunSpec protocol mostly focuses on "device level" communications (i.e., not specialized on clustering or "utility level" data). Consequently, being a suitable alternative for the local exchange of information occurring among inverters, as well as for their interactions with a CC, if required by the strategy.

Such protocol is mostly incorporated in the application layer, being at the top of the OSI model [20]. Since it is also based on the well-established modbus protocol, its implementation allows integration with most of the commercialized DERs technologies presenting communication interfaces. Yet, being on top of the OSI model, it supports different communication means (wireless, wired, optical fiber, etc), and it provides access to different data transmission approaches (P2P or PMP). For what concerns smart inverters, the SunSpec protocol defines a chained data model for the mapping of registers that follows the data transmission (i.e., different categories) defined in [15] and previously mentioned in Section II (i.e., placement of different data categories). This means that the protocol specifies which registers should be accessed for the reading/writing of: identification data, control variables, monitoring measurements and other operational data [28].

As an example, when an electrical quantity is required to be shared among inverters in a consensual strategy through SunSpec Protocol, each inverter must, as depicted in Fig. 4: *i*) identify its neighbors by reading and interpreting their ID headers (i.e., information comprised within the nameplate category); later, *ii*) know which specific register it should particularly read in order to attain the desired control variable (e.g., shared power [8]-[10],); and then, *iii*) adjust its local control references. Since the mapping proposed for the

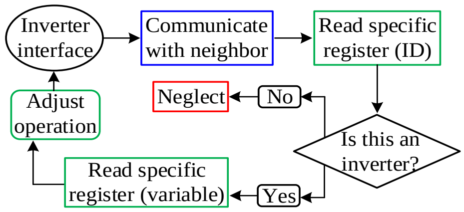

Fig. 4. Example of communication through SunSpec protocol in a general consensus-based cooperative strategy.

protocol is thoroughly described in [27], [28], it is not further discussed herein.

In [15], some additional technical features are defined, which demand, as compliance requirement, that an inverter using the SunSpec protocol should support, at least: *i*) TCP/IP implementation at the transport layer of the OSI model; as well as *ii*) RS-485 or Ethernet connectivity for the physical layer. This protocol also allows inverters to use low data-rate communication, comprising narrowband transmission with baud rates from 9600 bps to 115200 bps [27], which should be enough to fulfill the data transfer requirements of most of cooperative control strategies proposed for application in low-voltage MGs of small to medium size [29].

B. DNP3 Protocol

The DNP3 protocol [30], also known as IEEE 1815 – 2012 standard, is a widely used open protocol considered on higher level applications, mostly focused on data transmission within the power utility scale due to its particularly designed features and high immunity against noise. Yet, it has been widely used for the interface of DER devices with utility's supervisory systems (e.g., SCADA). Among many [30], some of the most significant features for the application of this protocol, particularly targeting cooperative control of inverters, are:

- *Broadcasting*: this is the most suitable protocol among the three comprised within [15] to transmit a single message to multiple dispersed inverters. This feature is highly notable for strategies like the ones within [10], [12] and [19];
- *Time-stamped data*: Accurate time-stamp can be performed regardless of the type of data being transmitted. Although other protocols, such as the SunSpec, are able to register time-stamps, they might not be as precise as DNP3 depending on the format of the data or the transmission rate of communication. This feature also is interesting for [10] and [19];
- *Accurate time synchronization*: Depending on the properties of the control strategy, synchronization techniques are required to timely align the communication among inverters to improve their coordinated operation. Hence, this feature may be suitable for approaches like the one in [31].

The infrastructure of the DNP3 protocol is set up mainly on the application and data-link layers of the OSI model. Even though it follows the categories defined within [15], it focuses on the formulation of groups of data according to their type (e.g., binary, analog, counter, etc), as well as to their feature of being part of the communication packet as an input (e.g., reading of a control variable) or output (e.g., a written variable to command the inverter). Also, data transmission is formulated by events, which is characterized by the occurrence of a significant change in the related system, or by an intended trigger on communication channels [30].

Compliance with this protocol is considered within [15] only comprising TCP/IP implementation and through Ethernet means. In addition, as evaluated in [32], DNP3 can perform data transmission with delays from 3 to 100 ms, depending on the type of message to be sent and the distances of the communicating nodes. This also encompasses expected latencies for data transmissions within MGs, of up to 100 ms, as discussed in [33]. Thus, in brief, this protocol should be a suitable solution for implementation of cooperative strategies, especially for approaches requiring a centralized controller, which could monitor and manipulate inverter's data just as already done by punctual utility related applications.

C. SEP2 Protocol

This last protocol, also named IEEE 2030.5 standard [34], is one of the most promising approaches employed for adequacy of data transmission means for DER-based systems. Beyond its presence in [15], it has been already incorporated as the default protocol within leading real applications of smart inverters and regulations such as the Rule 21 [35]. Such protocol focuses on the procedures and communication infrastructure for transferring data related to the monitoring and control of inverters. Its fundamental particularities are related to the application layer of the OSI model, taking advantage of TCP/IP to interact with the transport and internet layers, enabling the utilities to manage distributed devices in an integrated way [34]. One important feature to highlight is its flexibility to arrange data transfer links for supporting individual or grouped (i.e., clustered) inverters existing within the communication network. Additionally, other relevant features for MG control through cooperative inverters are:

- *Price data*: if desired, this protocol incorporates real time electricity pricing on the communicated data, which is an important matter to account while steering inverters to provide more economical gains, regardless if the focus is on the overall goal of MG or for single owners of DERs, as done in strategies [16], [36];
- *Communication to aggregators*: it is also possible to manage communication among several hubs or central units, allowing to coordinate clusters of inverters in different networks, aiming at providing higher dispatchability of MGs [12];
- *Cloud support*: since this technology is built to interact with the internet layer, it provides a singular capability to easily support communication interactions with cloud-based servers, which gives reinforcement for the implementation of strategies like [23].

The basic principle of interoperability behind the SEP2 protocol is the adoption of the RESTful architecture [34]. Hence, this communication infrastructure relies on a server-client interaction on which communication packets are formulated following the hypertext transfer protocol (HTTP) structure [20]. Although this protocol facilitates the provision of plug & play features for inverters, for such application, it may introduce latencies in communications on the order of 10's of seconds as stated in [37], which may not be suitable for cooperative strategies that totally rely on a centralized controller to provide fast frequency response.

A summarized comparison among these three protocols included in [15] is presented in Table I to demonstrate the main particularities among them. The adopted features within Table I are defined as follows. Regarding communication distances, the term "short" stands for maximum lengths of very few kilometers, "medium" and "long" refer up to tenths and hundreds of kilometers, respectively. Technology readiness indicates how consolidated the protocol is and how easily it can be found in commercial solutions in the electric sector. Finally, complexity of implementation is related to the required amount of code instructions. A brief discussion on constraints is then presented in relation to these protocols, focusing on their application on coordinating inverters.

TABLE I. SUMMARIZED COMPARISON OF THE PROTOCOLS IN [15].

Feature	Protocol		
	SunSpec	**DNP3**	**SEP2**
Application Range (Max. Distance)	Short to Medium	Medium to Long	Short to Long
Technology Readiness	Fair	Good	Good
Amount of Inverters Supported in a Communication Cluster	Small to Medium	Medium to Large	Large
Complexity of Implementation	Low	Medium	High

IV. DISCUSSION ON CONSTRAINTS

Although standards and regulations like [15] and [35] encompass the main required features of the SunSpec, DNP3 and SEP2 protocols, some concerns still need to be further addressed when it comes to their employment as means for coordinating distributed inverters. Firstly, taking into consideration the merit of interoperability, regardless of the scope of application of these protocols, inverter manufacturers must provide support to at least one of these technologies, in order to fulfill the compliance requirements within [15]. From the commercial point of view, such requirement is beneficial since it facilitates for manufacturers to choose whichever protocol fits better their designs. Nevertheless, by having different protocol technologies embedded in inverters, which are not directly compatible with each other, interoperability becomes likely constrained. For instance, in real applications of cooperative control a MG management system would certainly consider distributed inverters from different manufacturers. In [35], a similar limitation occurs since communication interfaces of inverters are not required to support compatibility with more than one protocol. However, on the opposite side, by imposing SEP2 as the default protocol, standardization is facilitated.

Cyber security is another very relevant issue related to the employment of communication in DERs and SGs [38]. Likewise, this matter should also be accounted on the establishing of data networks for transmitting data among inverters. Each of the three previous protocols within the scope of this work presents particular features in respect to encryption and how data can be securely transmitted. Beyond the already mentioned interoperability issues, [15] does not determine any requirement related to this matter and states that data security should be defined based on the deployment of the inverters, also proposing it to occur following a mutual agreement among the participating DER owners. Such undefined condition makes more difficult to form clusters of inverters in MGs, since there is not default operational settings to securely access an inverter's data (i.e., even among devices using the same protocols, different manufacturers may adopt particular cyber security settings that could possibility limit access to control information).

CONCLUSION

Communication infrastructures are addressed in this paper focusing on their applicability for cooperative control strategies of smart inverters in MGs. The communication requirements comprised within the recently updated IEEE

1457-2018 standard were taken as reference, leading to the highlighting of specifications from the SunSpec, DNP3 and SEP2 protocols. From discussions, it can be inferred that each of these technologies presents advantages and disadvantages upon different aspects, such as their main scope of application, the capability to accommodate different DER devices in a network, and how they formulate data transmission. Moreover, some critical comments remark that, although standards for the electrical sector are incorporating communication requirements to achieve higher interactivity among inverters, significant improvements are required in terms of interoperability. Standardization on cyber security is also critical and should be further evaluated.

As final remark, the adoption of the SunSpec protocol is seen, by the authors' point of view, as the most prominent technology to be employed on applications related to cooperative control of inverters in MGs. This is due to the flexibility of the approach to support low latency data transmission, which is structured on the device level. Additionally, through the mapping of registers provided by its data model, standardization of communication among inverters from different manufacturers might be facilitated, supporting higher interactivity and plug-&-play features.

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