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CURRENT CHALLENGES AND FUTURE TRENDS IN THE FIELD OF COMMUNICATION ARCHITECTURES FOR MICROGRIDS

Abstract

The concept of microgrid has emerged as a feasible answer to cope with the increasing number of distributed renewable energy sources which are being introduced into the electrical grid. The microgrid communication network should guarantee a complete and bidirectional connectivity among the microgrid resources, a high reliability and a feasible interoperability. This is in a contrast to the current electrical grid structure which is characterized by the lack of connectivity, being a centralized-unidirectional system. In this paper a review of the microgrids information and communication technologies (ICT) is shown. In addition, a guideline for the transition from the current communication systems to the future generation of microgrid communications is provided. This paper contains a systematic review of the most suitable communication network topologies, technologies and protocols for smart microgrids. It is concluded that a new generation of peer-to-peer communication systems is required towards a dynamic smart microgrid. Potential future research about communications of the next microgrid generation is also identified.

1. INTRODUCTION

The basic structure of the electrical grid has almost remained unchanged up to now. For decades the grid has delivered energy from remote power plants towards consumer loads in a unidirectional and centralized manner [1]. Currently, the generation, distribution and consumption of electricity is evolving at an impressive speed, driven by both the high penetration of distributed energy resources (DERs) that are being incorporated to the grid and the advances in information and communication (ICT) technologies. In this context the microgrid concept has emerged. A microgrid forms an autonomous power system that needs a ubiquitous information layer for coordination, monitoring and control of all the distributed energy resources deployed in it. Nowadays, most microgrids still rely on legacy communication networks. However, microgrid energy systems are transitioning from centralized systems towards distributed energy systems with more demanding reliability, security, and performance requirements. Therefore, a flexible and adaptive communication network architecture is required. To make effective decisions, power designers will need a basic understanding of communication network technologies that should be implemented on microgrids. Consequently, a description of the past, current and future trends as well as the fundamentals about communications for deploying intelligent microgrids is included in this paper. The basics of today’s communications in microgrids are also described. Next, the main challenges in the communication requirements of intelligent microgrids are defined, leading to the proposal of a new generation of smart microgrids. The most suitable communication architecture (network topologies, communication protocols and technologies) for the deployment of this proposal is discussed. Next, a new generation of peer-to-peer (P2P) communication systems for the future microgrids is proposed. Finally, new research topics for the transition to future microgrids are shown.

2. TODAY'S MICROGRID STATUS

A Microgrid (MG) (Figure 1) is a low voltage distributed network of individual consumers within a building, campus, or community that are interconnected with, at least, one shared distributed generation source (DG). A microgrid consists of a variety of loads, microsources (MS) and energy storages systems (SS), called distributed energy resources (DERs), that acts as a single controllable entity with respect to the main grid [2], [3], [4]. Microgrid operates mostly connected to the main distribution network but they can be automatically disconnected from the main grid at the point of common coupling (PCC) in case of faults to provide a minimum level of service during a utility grid power outage. They can be reconnected once the fault has disappeared [5], [6]. Microgrids must have their own control to ensure the correct operation and coordination of the different DERs. A Microgrid Controller (MGC) is usually needed to manage the operation within the microgrid, the energy flows and the interconnection with the main grid. In addition, all microgrid devices need to communicate with the MGC.

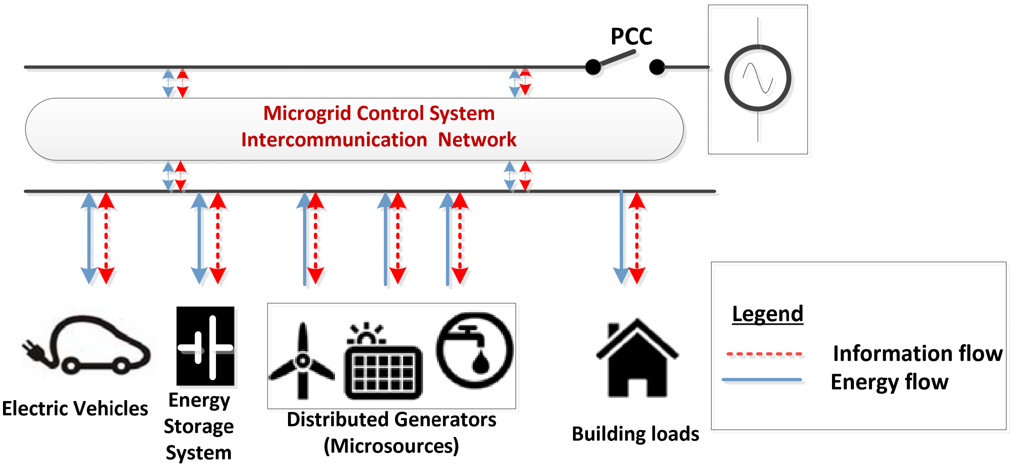


Fig.1. Simplified scheme of a microgrid with a Microgrid Controller

Traditionally, this control is carried out by means of a three level hierarchical scheme [7], [8]: (Figure 2): Distribution Management System or tertiary control (DMS), Microgrid Central Controller (MGGC) or secondary control and load control (LC) or primary control [5], [6], [9].

- Primary Control: This level of control operates in the time range of milliseconds to minutes, and reacts to the transient dynamics of the DER and the system to respond to any instantaneous deviation in the system's voltage or frequency. This controller acts as local control for each DER unit and utilizes local measurements and responds to short-term events such as islanding detection, sudden real and reactive power mismatches, and power sharing.
- Secondary Control: This level of control operates in the time range of minutes to hours, and it comprises the discrete dispatch of DER. This level is controlled by the MGCC. This controller is responsible for the optimal coordination and operation of the whole components connected in the same microgrid, assuring the overall maintenance of the grid parameters in both connected and island mode. The secondary control also incorporates control strategies and operations such as intentional islanding, resynchronization, and load shedding.

- Tertiary Control: This level of control operates in the time range of hours to days, and it involves the communication with the different microgrid central controllers (MGCCs), and management of the MG when it operates on the market. The main entities in this level are the Distribution Network Operator (DNO) and the Market Operator (MO) who are delegates of the main grid.

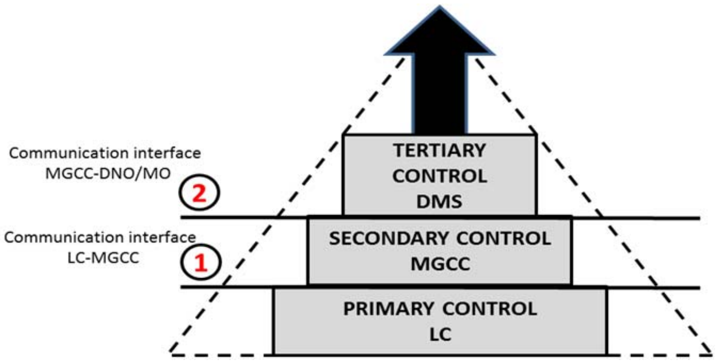


Fig.2. General Hierarchical Architecture of MG control. Communication interfaces for stablishing MG control.

Control strategies need communication networks or links between the different levels to achieve an optimal microgrid operation. Communication interfaces must be created to establish a bi-directional communication channels that allows information transfer between the different controllers [10]. (Fig.2, ① and ②). Generally, data flows between nodes in both directions, i.e., each node are able of receiving and forwarding data over links with other nodes or endpoints. The nodes in microgrids are created by adding information and communication capabilities to the underlying distributed energy resource or component, giving rise to intelligent electronic devices (IEDs) [11]. In this way, the microgrid controller may communicate with IEDs and other components to provide them data or control commands.

For a successful information exchange between nodes within a microgrid system, predefined procedures or protocols for data transmission regulation are needed. A protocol suite consists of a layered architecture where each layer is assigned to a set of functions using one or more protocols [11]. Data communication networks commonly use multiple levels of protocols based on ISO-OSI (International Standards Organization/ Open Systems Interconnect reference) model [12] (seen Figure 3). This allows to convert the information in a form that can be transmitted. Thus, regarding communications, the effectiveness of the control and the communication microgrid infrastructure is linked with the microgrid control scheme and its communication architecture.

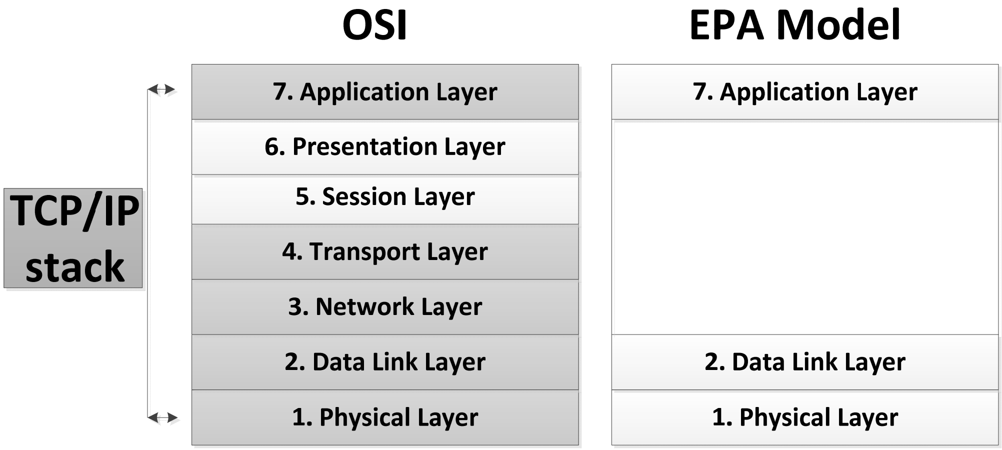


Fig. 3. OSI Reference Model, EPA model and TCP/IP model

Today's microgrid installations use centralized architectures to implement the three level hierarchical scheme and achieve data transfers between entities. In these architectures power is delivered in a unidirectional way and consumers have a passive role characterized by non-controllable loads, lack of predictability and null contribution to the system management.

These centralized architectures where a central controller communicate with all microgrid resources and make decisions has been implemented, for many years, by Supervisory Control and Data Acquisition (SCADA) systems [13] which uses the Enhanced Performance Architecture (EPA) model [11] . EPA has three layers (1, 2 and 7) instead of the seven layers defined in the OSI model as depicted in figure 3. This fact reduces the services offered by the EPA stack protocol. Otherwise, SCADA use direct communication links (i.e. no internet) [11] to send and receive commands and data through various protocols. Some of the most popular protocols in the electrical sector are MODBUS, PROFIBUS, CANBus or DNP3. All of them are generally based around Client-Server (Master-Slave) architectures with bus network topologies, [11], [14], [15].

Recently, there is growing a trend towards the use of new communication technologies based on internet or on Common Information Model (CIM). The Internet architecture is based on TCP/IP protocol. TCP/IP is an easy solution to the problem of achieving end-to-end communications [16]. TCP/IP protocol suite is used by Internet. The TCP/IP stack normally has four layers: Physical and Data Link layer (Link layer), Network, Transport and Application layers [Figure 3, TCP/IP stack]. These protocols are now starting to be used in electrical control systems and it is evidenced by the evolution of the Industrial Protocols, that were previously cited, such as Modbus, DNP3 and Profibus towards Modbus/TCP, DNP3 over TCP and Profinet, respectively, for their integration on the traditional SCADA. These protocols exploit the benefits of TCP/IP to upgrade their capabilities. For instance, in the case of Modbus or Profibus over TCP/IP communication systems, they are reported undesirable events as incorrect address, packet failure, illegal function code received, etc. Besides the aforementioned properties, DNP3 over TCP/IP supports timestamps and data quality information that can be included in the messages [11]. However, despite these improvements, the centralized control based in client-server communication architectures cause inefficiencies in the communication microgrid system, provoked by several causes: On one hand, a failure in the centralized control point could lead on several faults or even shut down the entire system. On the other hand, the nodes (slaves) are not able to start a communication themselves with the master. In addition, there are difficulties to manage data in real time of a wide range of devices [17], [18]. As a result, these disadvantages can lead to provide poor services, bottlenecks or under-utilization of the network resources.

An alternative technology to be used in microgrids is Power Line Carrier (PLC). PLC technologies use the electric power lines as a medium that enable the bidirectional data exchange. It provides a vast coverage and in terms of infrastructure is the most cost-effective technology since the lines already exist. In recent years, microgrids activities have brought a lot of attention to PLC technologies. As an example, the microgrids installed in the University of Seville and NUAA in China, uses PLC as a communication medium for information management and transmitting data [19] . However, PLC technology has negative effects in the communication channel such as a noisy medium disturbed, distortion, frequency impedance alterations and the risk of signal attenuation [20].

The increasing introduction of distributed energy resources into the power grid changes the current scenario, because the incorporation of micro-generation allows bidirectional power flows and active consumers, i.e., the end users change their role of passive consumers to active prosumers. Consequently, immediate solutions about microgrid communication architectures that cope with these changes and enable high performance data delivery and real-time monitoring and control are needed, leading to reliable, resilient and sustainable microgrid control systems.

3. TOWARDS AN INTELLIGENT MICROGRID

It has been noted that communication system used in today's microgrid has important inefficiencies and it is also localized to support the integrated communications needed for the modern power grid (smart microgrid (SMG)). However, energy systems are increasingly distributed. The integration of DERs into the energy system cause many challenges into the communications field. To incorporate more renewable and alternative energy sources, the communication infrastructure must have the ability to easily handle an increasing amount of data traffic or services requests and must provide a real-time monitoring and control operation of all these nodes. Current serial communications deployed in SCADA systems refer to a set of legacy standards that are still used for low data rate applications and asynchronous bit transfer. Since microgrid operations need timely control actions, a Real-Time Measurement Parameters (RTMP) function is required [21]. To reach this goal, it´s mandatory to know which bandwidth and which latency (delay) can tolerate each microgrid application [22], [23], i.e., each microgrid function has its own latency and bandwidth requirement depending on the kind of system response it´s dealing with [12], [24], [25]. The IEC 61850 and IEEE 1646 standards [26], [25] give specifications for these requirements. The network performance requirements for each microgrid application have been summarized in Table 1. Moreover, the expected communication delay of each kind of microgrid message was specified in [27], being summarized in Table 2.

Microgrid Messages	Bandwidth	Latency
Demand Response	14-100 Kbps	500 ms-several minutes
Distributed Energy Resources and Storage	9.6-56 Kbps	20 ms-15 s
Distributed Management	9.6-100 Kbps	100 ms-2s

Table 1. MG application and network requirement

Microgrid Messages	Delay Requirements
Protection information	4 ms
Monitoring information	1s
Control information	16 ms-100ms
Operations and maintenance information	1s
Messages requiring immediate actions at receiving IEDs	1A:3 ms or 10ms;1B: 20 ms or 100 ms
Continuous data streams from IEDs	3ms or 10 ms
Synchronization messages	(Accuracy)

Table 2. Microgrid Message Type Delay Requirement for different microgrid functions (from [27]).

The communication infrastructure in the microgrid must satisfy these timing requirements, because a low bandwidth can lead to bottlenecks, loss of data packets and distortion. Besides, if the communication delay exceeds the required time, the information does not fulfill its purpose and, in the worst case, electric damage in the microgrid could happen [4]. In this regard, the underlying communication system needs to be designed with network performance requirements to meet the needs of time sensitive data streams, bandwidth and latency, among others. To satisfy this network performance requirements that smart microgrid traffic requires, Quality of Service (QoS) is needed. The Quality of Service concept is the network ability to provide priority treatment for communication packets of certain critical microgrid applications. QoS management is needed for distributed control and protection microgrid applications that have severe delay requirements and need to deliver information in an acceptable amount of time. For instance, the stability of the closed-loop while performing bilateral load following (with sampling rates typically in the range 100–1000 ms) is highly dependent upon the latency (delay), variability in latency (jitter), and packet losses that the control network induces [28]. Therefore, when networks exceed their capabilities to transfer, store and buffer data, packet loss and low delivery rates are experienced. As a result, when the network faces congestion due to dense data traffic, QoS allows a preferential delivery service for the most critical applications by ensuring sufficient bandwidth, latency and reducing data loss. QoS information is stored within the packet header in the form of a type of service (ToS) field to specify the class of service of each packet. Thus, based on the ToS byte, if there is a packet in a high priority queue, it´s served before the packets in low priority queues.

Besides, the increasing number of renewable energy sources and microgenerators as well as the integration of a large amount of DER units in the microgrid has an impact on the scalability of the communication system [8]. The main problem regarding the control of a wide number of DERs is that a failure of a device or a software error could bring down the entire system [29]. Furthermore, in networks with a high volume of devices is usual to add/remove devices to/from the network very frequently, therefore networks must be flexible enough, allowing the fluctuations of the number of devices and avoiding disturbances or instabilities. To cope with these potential failures, the system requires a certain level of redundancy, e.g., backup channels, software components and devices, etc. Critical functionalities in a smart microgrid demand more stringent availability requirements. It is worth pointing out that most network service providers (NSP) applications require less than 99.99% uptime, compared with 99.9999% for smart grids [20]. To achieve reliable and robust networks, the communication infrastructure must avoid link errors, routing problems, overloads, etc. Current SCADA systems cannot make these data available in a timely manner due to their limited bandwidth [30]. Thus, this capability requires the combination of advances in computational and analytical methodologies and self-healing protocols. In this context, Software Defined Networking (SDN) has emerged as a flexible, effective and reliable communication framework and as a power solution for the future communication network of the energy internet [31], [32]. This solution provides support for the dynamic, scalable computing and storage needs of complex digital networks by software and allows adaptive control and operations of networks in a cost-effective manner. These characteristics are favourable for developing hierarchical communication network architectures which allow to decouple control plane (which decides how to handle the traffic) from data plane (which forwards traffic). Moreover, SDN allows self-healing and self-organization [33] required features for the future smart microgrid developing.

The integration of networking and communication technologies in microgrids may cause vulnerabilities of cyber attacks. In addition, due to the increase number of distributed energy resources in the grid, the attack targets are also rising, producing more access points to disrupt the grid [34]. Thus, a microgrid needs to be robust against security attacks. To guarantee a proper protection, it´s necessary to minimize the ‘attack surface’ and to decrease the security detection response time, increasing the amount of effort required to violate the network in order to guarantee a proper protection [35]. The security architecture for SMG communication networks should be divided into different levels and zones such as device level (e.g. recovery from attacks), system level (e.g. access control, authorization, encryption, authentication, …) and organization level (e.g. policies, mechanisms, …). As a result, protocols should be designed and adopted by the communication system in order to identify and correct weaknesses in their physical and cyber security parameters.

In conclusion, the implementation of smart microgrid concept and its optimal and efficient control architecture become a necessary for integration of a high volume of DER. For achieve that, the intelligent microgrid requires information and communication technologies. However, despite the urgent need to materialize the intelligent microgrid there are several challenges should face to ensure this new communication architecture addresses: i) Real-time operation and network performance requirements such as latency, bandwidth and QoS mechanisms, ii) Reliability: flexibility and availability to manage a large amount of DER, iii) Cybersecurity issues

4. DECENTRALIZED GENERATION IN MICROGRIDS

To evolve towards development of smart microgrids satisfy the requirements above mentioned in Section 3 is mandatory. For reaching these objectives, the grid should move from a centralized infrastructure to a decentralized one. The decentralized communication infrastructures remove the centralized controller as a single point of failure and therefore produce an improvement in the reliability of microgrids. In this structure all devices are able to control themselves independently as opposed to a “master” controller, i.e. each DER unit is considered as an agent. An agent is a computer system able to do tasks on an autonomous way and with capabilities to communicate with their neighbor nodes for solving problems through cooperation, coordination and negotiation [36]. As a result, the centralized hierarchical management scheme presented on Section 2 could be implemented employing a decentralized architecture. This section presents relevant distributed communication topologies, communication technologies and protocols to tackle the design of a communication distributed architecture for a microgrid.

4.1. Distributed Communication Network Topologies for Smart Microgrids

Nodes or agents network topology in decentralized architectures is crucial in terms of developing an efficient and appropriate microgrid. According their logical topology and degree of decentralization, distributed networks can be broadly classified into the following architectures [36], [37] , [38], [39] (Figure 4):

- *Centralized:* This topology uses a central server node to store nodes resources and information as well as act like an agent to coordinate actions among theirs. Nodes send messages to the central server to determinate the addresses of nodes that contain the required resources/data. However, like a decentralized system, once a node has the information, it can directly communicates with the searched node without help of the central server. In this structure, the agents have an increased intelligence (compared with typical nodes of the communication network) and improved communication capabilities. Additionally, some control tasks are distributed through agents, although they still have a lack of decision-making capabilities. Moreover, centralized distributed topologies still have a unique point of failure, scalability limits, performance degradation and lack of robustness.

- *Hierarchical:* This topology is characterized by having some agents (super nodes) that take authority over the actions of other agents. In this network exists various agents that carry out different hierarchical tasks. Most microgrid deployment in literature employs a three-level hierarchical architecture where, generally, top -level agents are responsible for critical decisions, middle-level agents make decisions about connected or disconnected grid tasks and the lower-level agents interact with sensors and devices. The choice and allocation of these super nodes is dynamic. This approach is still unreliable due to not all peers can act as super-nodes by a lack of resources.

- *Distributed:* In a distributed communication topology, each local agent is autonomous, has the same role in the network and is responsible for acquire knowledge about its own part of the network. A significant difference regarding the other architectures is that individual agents are allowed to discover other agent information through communication and coordination with their neighbors. This topology do not uses a central server to manage the network avoiding a single point of failure and allowing a very high scalable network.

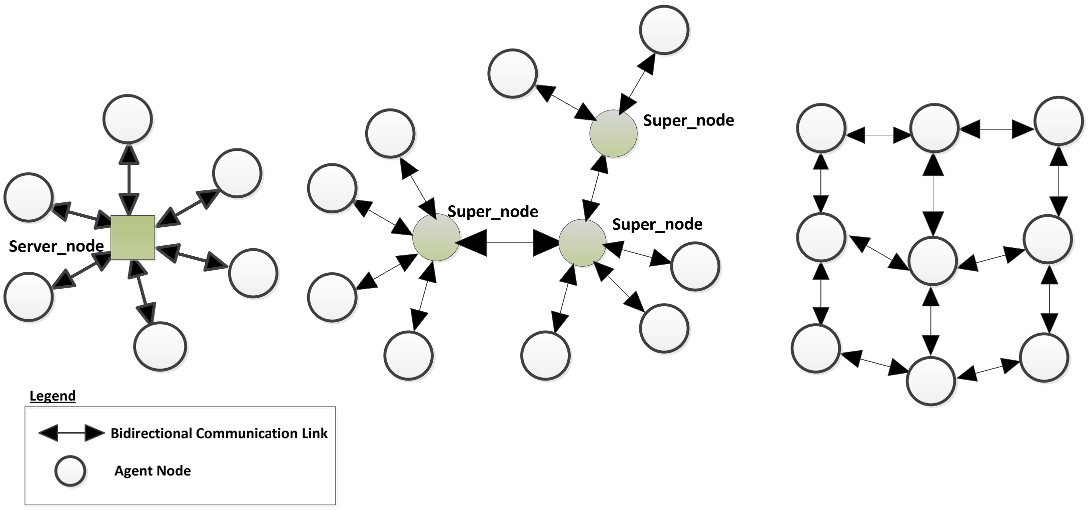


Fig.4. Decentralized architectures for microgrid control: Centralized, Hierarchical and Distributed.

The selection of the appropriate network topology has have an important impact on the information flow, on the performance and on the capability of the microgrid network to be expanded and updated. Fully decentralized topologies present several advantages among the others, as it´s been described above. Distributed centralized topologies are acceptable in microgrids where a pre-defined operator manages the microgrid and the generation and consumer sides of the power system have similar goals. The central server receives status information from all the units and can calculate an optimal global control strategy, providing a practical implementation of the control infrastructure and reducing the implementation costs. Nevertheless, decentralized control is the most suitable method when there are multiple energy devices on the generation and consumption sides to be managed, requiring real-time monitoring and adjustment. In this case, a centralized control could not meet the requirements. Although the installation costs of decentralized control topologies are higher than those of centralized control, the operation costs are greatly reduced and it can be amortized in a short time [40]. In addition, in decentralized networks it´s possible to install modular and scalable systems with a good precision.

4.2. Distributed Communication Technologies for Smart Microgrids

A distributed network is a collection of nodes placed at remote locations over a geographical area and connected through communication links for data transmission among the agents under operation. A link may be realized by means of different communication technologies supported by two main communication media, wired and wireless. The choice of the communication medium technology has its associated advantages and disadvantages that designers should evaluate. Therefore, one key aspect of smart microgrids communications design is to deploy suitable and future-proof wired/wireless technologies.

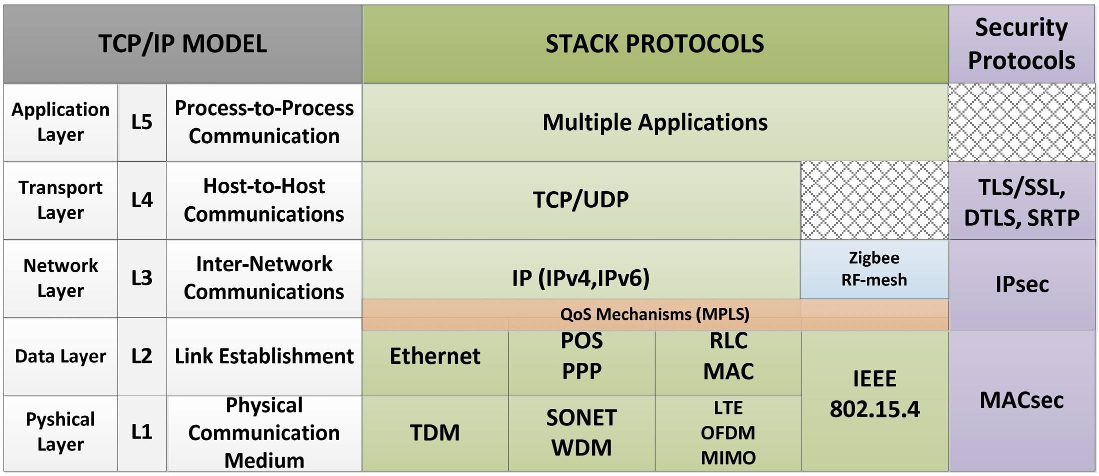
Traditionally, wired communications have been employed to transmit information through the electrical grid due to their better performance than wireless technologies regarding robustness, reliability, security and bandwidth properties. However, wired technology involves higher deployment cost. In addition the network expansion schemes become more complex. Some popular wired technologies used in microgrids are serial communication RS-232/422/485 for SCADA systems [23], Ethernet (IEEE 802.3 technology), bus based technologies (e.g. ModBus, ProfiBus) and Power-Line Communication (e.g. DLC, PLC, BPLC) [41]. However, except of Ethernet, these technologies cannot provide decentralized communications in a reliable manner. The possibility to implement Ethernet over microgrid systems were reviewed very recently by [42], [43]. These works demonstrates Ethernet's applicability for DER's data exchange allowing share bandwidth to all connected devices and it demonstrates that Ethernet can be used in a real time as well as a great scale.

By other side, in spite of their (in general) lower performance in terms of robustness, the wireless technologies are increasing their security capabilities and could be an interesting solution for distributed microgrid communication links because of the cheaper installation costs. Depending on the network coverage, distinct groups of wireless network technologies can be identifies: WPAN (Wireless Personal Area Network), WLAN (Wireless Local Area Network), WMAN (Wireless Metropolitan Area Networks) and WWAN (Wireless Wide Area Network). The most popular solutions for wireless internet access in microgrids are [44]: Family standards IEEE 802.15 (Wireless Personal Area Network, WPANs), especially IEEE 802.15.4 standard (Low-Rate Wireless Personal Area Network, LR-WPAN) that defines the specification for low rate, low power, low complexity and short ranges or IEEE 802.11, Wi-Fi (WLANs). They are networks to cover small amounts of information over relatively small distances. Both technologies could be used to perform the links either between DERs at primary level and/or between DERs and MGCC at secondary level on the hierarchical microgrid control scheme. By other side, cellular networks (4G/3G/HSPA, LTE (Long-Term Evolution), LTE-A (Long-Term Evolution Advanced), and Evolution–Data Optimized) could be used for implementing links at tertiary level and/or between different microgrids [45].

The Wireless technologies listed above provide communication between nodes in a single hop. However, multi-hop technologies may be assumed a key function in microgrid network control research due to they allow to extending the coverage of a wireless network over multiple wireless hops. Mobile Ad-hoc Networks (MANETs) or Wireless Mesh Network (WMNs) are wireless multi-hop networks. An ad-hoc network is a collection of independent nodes that communicates without infrastructure support using wireless links. In this networks nodes operate as both host and routers, in other words, can act as a router to transmitting data of its nodes. Similar to the MANETs are WSNs that have been created to resolve limitations as well as improve the performance of WPANs, WLANs, WMANs, WWANs and MANETs in general [46]. These are networks composed with multiple Mesh Access Points (MAP), usually stationary points, that create mesh topologies whose aim is provide access to different infrastructure networks [47], for example clients in ad-hoc network operating in WI-FI network cannot access in a different radio technology network such as WPANs or other networks, while in case of WMNs both network access are possible through mesh routers. This characteristic is very important in order to achieve interoperability between microgrids. Examples of this kind of microgrids have been study in [48], [49], [50], [51]. This reviews determined that mesh networks offer higher levels of redundancy and robustness in terms of data communications in case of link degradation, failure or loss of node, either temporary or permanent very important characteristics for microgrids deployments. Multiple hops can be used to achieve a more balanced distribution of traffic over network [52], [53]. In fact, the wireless technologies presented before, are now including support for multiple-hop communications which is the case of the IEEE 802.15.4g (mesh network solution for smart metering) [54], IEEE 802.15.5 (mesh network for WPANs/ZigBee) [55] and 802.11s (networking capabilities to Wi-Fi) [56]. It is important to point out that exists the possibility to use this technique in cellular networks (4G or LTE) to achieve increasing the coverage or the capacity in the cell [57].

4.3. Main Distributed Smart Microgrids Networking Protocols

To allow communications in a distributed network it´s essential to specify the set of protocols to be implemented in each node. The decentralized communication networks used in microgrids are focused on the implementation of suitable Transmission Control Protocol/Internet Protocol (TCP/IP) [58]. Current TCP/IP based communication systems provide a high enough bandwidth and real time monitoring and control of smart microgrids. Moreover, smart microgrids can deploy their "utility-Intranet" to obtain full control on communications with increased flexibility, security and reliability. The design of a client-server architecture for power grids using TCP/IP for information transmission has been discussed in [59], [60]. For communication between two endpoints a protocol stack development is mandatory. In this section, the main layered protocols that could be used to deploy distributed smart microgrids are described. Figure 5 depicts both the main communication purpose at each layer in the TCP/IP protocol stack and the main networking protocols used in a Microgrid Control System.



TCP/IP MODEL			STACK PROTOCOLS				Security Protocols
Application Layer	L5	Process-to-Process Communication	Multiple Applications				▨
Transport Layer	L4	Host-to-Host Communications	TCP/UDP			▨	TLS/SSL, DTLS, SRTP
Network Layer	L3	Inter-Network Communications	IP (IPv4,IPv6)			Zigbee RF-mesh	IPsec
			QoS Mechanisms (MPLS)				
Data Layer	L2	Link Establishment	Ethernet	POS PPP	RLC MAC	IEEE 802.15.4	MACsec
Pyshical Layer	L1	Physical Communication Medium	TDM	SONET WDM	LTE OFDM MIMO		

Fig.5. Communication and security common microgrid protocols stack in the TCP/IP model

<u>Link Layer:</u> This layer describes the operational physical and data link network functions. The Physical Layer (L1) is the medium used for the transfer of data. The Data Layer (L2) is used to establish a link between two nodes. As described before, distributed smart microgrids accept different communication technologies, wired and wireless. Regarding wired technologies, the control systems implemented in microgrids generally use the Ethernet protocol (IEEE 802.3) for fast and reliable operation, but the cost to develop this kind of network is expensive for long distance communications. Typically, the Ethernet protocol is coupled with the Medium Access Control (MAC) protocol, a sublayer of the L2 link layer. The MAC sublayer, in addition to the receive and transmit data frames, assigns addresses to each connected microgrid device. Commonly, these type of wired networks (coaxial cable or twisted pair) uses TDM (Time

Division Multiplexing) as L1 protocol. TDM is a digital processing method that allows to share the total bandwidth among different connections. This is achieved through putting multiple data streams in a single signal by separating the signal into many segments, each one having a very short duration.

In smart microgrids over fiber optic networks, WDM (Wave Division Multiplexing) or SONET (Synchronous Optical NETwork) also called Synchronous Digital Hierarchy (SDH) are the protocols used in L1. WDM is a method which combines multiple signals on laser beams at various infrared (IR) wavelengths for their transmission along fiber optic media. Besides, SONET is a high data rate protocol (up to 40 Gbps) originally developed for voice communication over optical fiber networks. The L2 protocol for SONET is typically 'Packets over SONET'/SDH (POS). POS employs the Point-to-Point Protocol (PPP), a common L2 protocol used to establish a direct connection between two nodes that can simultaneously support multiple L3 network protocols including TCP/IP. The use of fiber optic technologies can multiply the effective bandwidth of a fiber optic communications system by a large factor, but its cost must be studied for its implementation in microgrids against the alternative of using Ethernet technologies into a cable [61], [62], [63]. Nowadays, the use of Ethernet in LAN is very common and has evolved to support high data rates over long distances, such as metropolitan area networks (MAN).

Recent advances in wireless communications with easy installation, low cost and acceptable transmission speed make this technology be viable for microgrid monitoring and control. For their implementation, two protocols can be used. L1 protocols, such as LTE, are used when they run on fourth generation cellular networks (4G). Protocol 802.14.5 is the common choice when ad hoc communication networks composed of radio nodes are used. LTE uses an L1 protocol called orthogonal frequency-division multiplexing (OFDM) to enable simultaneous two-way communications. LTE also employs multiple input and multiple output (MIMO) to multiply the capacity of individual radio links by using multiple transmit and receive antennas to exploit multi-path propagation of signals. L2 layer in cellular networks, LTE has a MAC sublayer that acts as interlinking with the RLC (Radio Link Control) sublayer that performs packet segmentation and flow control among entities. RLC also supports end-to-end IP connection. The L2 layer for ad-hoc networks support Radio Frequency Mesh (RF-mesh) such as IEEE 802.15.4g or IEEE 802.15.5. For smart microgrids applications the predominant RF-mesh standard is Zigbee (IEEE 802.15.5). Zigbee enhances the IEEE 802.15.4 standard by adding networking and security functions required for smart microgrid applications.

Additionally, in Section 3 it´s been pointed out that a communication infrastructure with Quality of Service (QoS) requirements is absolutely needed. Consequently, microgrids should adopt suitable mechanisms to guarantee QoS. In telecommunication networks, QoS differentiation is achieved through resource reservation and traffic prioritization [20]. These characteristics are implemented at a "layer 2.5" protocol, as it performs the functions of L1 and L2 while also including features that are typical of L3. For carrying out QoS implementation in communication networks, many families of standards define the medium access control (MAC) layer with the specification of different traffic categories. However, Internet by itself cannot assure QoS requirements, because the best-effort level of service for the delivery of data is the rule in today's Internet [64], [65]. Therefore, traffic handling mechanisms must be implemented in microgrid networks at “2.5 layer”, using protocols such as Integrated Services (Intserv), Differentiated Services (Diffserv), Multiprotocol Label Switching (MPLS), IEEE 802.1p/q tags (QoS mechanism on Ethernet) and IP Precedence [66], [67]. These several QoS services allow a single network to satisfy different types of traffic by emulating many L1 and L2 protocols including T1, PPP, Frame Relay, and Ethernet.

__Internet Layer:__ The Internet Layer (L3) controls the operation of packet transmission by assigning addresses to nodes and routing frames along physical paths. The Internet Protocol (IP) is the most widely implemented networking layer protocol. Although the Internet is based on IP, the protocol is also used on networks unrelated to the Internet. IP enables end-to-end smart microgrids applications to communicate to any two endpoints that have at least one or more networks providing a data path between them by using various networking technologies, i.e., IP can operate independently of the underlying physical media, L1 and L2 layers. This characteristic provides interoperability among third-party non-compliant end devices and compliant communications networks. This allows much greater flexibility for interoperability as utilities implement their Smart Microgrid network. Therefore it plays a vital role in unifying the information while allowing utilities to select the communications technologies and end devices (meters, IEDs, etc.) that make the most sense for them. Network interoperability is indispensable in order to achieve an overall optimal system operation and connectivity, independent from the used physical medium, the type of devices and the manufactures [68].

IP is available with either of two versions (IPv4 and IPv6). In both versions, every system (node or endpoint) is identified by its unique network layer address, but the main difference between both IP versions is their respective host addressing systems: IPv4 uses 32-bit, whereas IPv6 uses 128-bit addresses. However, the version of IP currently deployed in most microgrid networks is IP version 4 (IPv4). Despite of this, microgrid network planning should consider future migration to IPv6, because the distributed energy resources (DERs) in the grid may need their own individual IP-address in the future. Currently, many investor-owned utilities have millions of electric meters installed. Other devices must be additionally considered, including an important amount of electric vehicles as potential roaming users in the future. That means that IPv4 might not have enough IP addresses for each of these large number of endpoints [69]. Additionally, multicasting is supported by IPv6 and introduces new features to QoS capabilities [70].

__Transport Layer:__ The transport protocols (L4) enable host-to-host communications. The two most common transport layer protocols are the Transmission Control Protocol (TCP) and the User Datagram Protocol (UDP). TCP is a connection-oriented protocol that provides reliable, sequenced, and error-checked delivery of a stream of packets between application endpoints. TCP is optimized for accurate and reliable delivery of packets rather than timely delivery, thus yielding relatively long delays. UDP is not connection-oriented, not providing any guarantee on packet delivery, but is highly time-sensitive [71]. The choice of the best suited protocol within a microgrid control system network depends mainly on design requirements based on the importance of speed versus reliability and on the need for error detection [11]. However, since the microgrid application requires reliable communications, TCP is the best option to be implemented [59]. On the contrary, shortcomings of TCP in performing congestion control for a large number of data sources and its inherently delayed acknowledgement could be ineffective for SMG control which can produce useless retransmissions of packets and throughput degradation [20], [60]. As a consequence, a large number of transport protocols and mechanisms have been proposed in order to improve the transport services offered to applications and to optimize the usage of the different technologies. For example, SCTP (Stream Control Transmission Protocol) and DCCP (Data Congestion Control Protocol) have been proposed to support the nodes mobility in the network [72] but these protocols are insufficient to address the transport characteristics of the nodes in the microgrid due to some intermediate nodes or Network Address Translation (NATs) may be not fully aware about these protocols (at the network level), which could lead to a blocking packets at the processing [73] and therefore a sub-optimal microgrid operation. These problems have motivated researches about development of novel protocols for their application in microgrids. Some of these are: SSTP (Scalable Secure Transport Protocol) and MPTCP (Multi-Path Transport Protocol) [74], [75], [76] that have been customized for grid data collection. By other side, for enhancing performance network mechanism, TCP-splitting is, nowadays, the most used approach in microgrids [60].

<u>Application Layer:</u> The application layer (L7) contains the protocols that support process-to-process communications, i.e. serves as the network interface for users and applications. It contains a variety of common functions such as resource sharing, remote file access, directory services, electronic messaging, etc. For microgrid network management, common application protocols like Dynamic Host Configuration Protocol (DHCP), Domain Name Service (DNS) or Network Time Protocol (NTP) can be used. Also specific protocols such Distributed Network Protocol (DNP3), Modbus, Profibus over TCP/IP or proprietary vendor specific protocols could be used [71]. However, for reliable and scalable communication architecture, interoperability is needed. In the field of the Microgrid, international standards have defined for achieve these interoperability at application layer. The most important of them are listed in table 3.

Reference Standards	**Detail**	**Application**
IEC 61850 (61850-7-420) [77], [78]	Communication between devices in transmission, distribution and substation automation system	DER/microgrid
IEC 61968 [79]	Data exchange between device and networks in the power distribution domain	Energy management system
IEEE 1547.x [80], [81]	Interconnecting DERs with Electric Power System	DER/microgrid
IEEE 1646 [82]	Communication Requirements	Substation Automation

Table 3. International Standards for MGs Networking/ Communications

The IEC 61850 is the most promising standard for design power communication networks [83], [84]. This standard has been proposed to increase the reliability and availability and to ensure interoperability. This standard use a communication model based on protocols such as Manufacturer Message Specification (MMS) for communication messaging, Simple Network Time Protocol (SNTP) for time synchronization and Generic Object Oriented Substation Events (GOOSE)- Sampled Measured Values (SMV) for fast messaging. It can operate over TCP based on implementing Ethernet [85]. The communication stack mapping the IEC 61850 services with the TCP/IP model layer is shown in Figure 6.

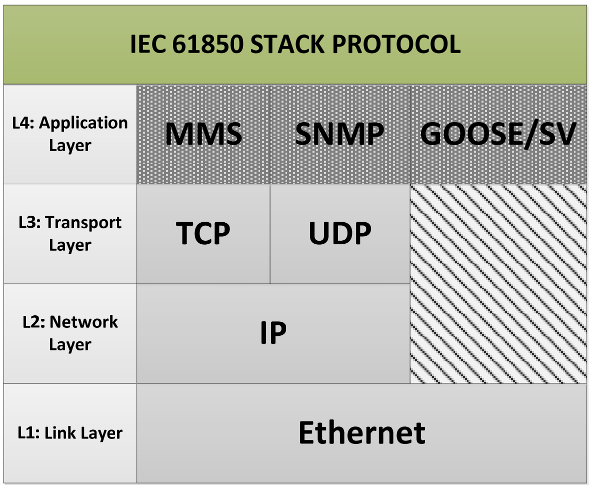


Fig. 6. Typical IEC 61850 Ethernet-based communication TCP/IP stack.

***Security Protocols**:* A microgrid control system network, apart from cyber-security mechanisms to prevent attacks, need protocols to provide network security (such as authentication and encryption). Security Protocols have to be end-to-end, lightweight, and scalable and prepared to be added at any layer to protect data transmitted between different microgrid applications and host. There are many end-to-end security protocols that can apply to microgrids networks and they can run over IP to ensure end-to-end security communications [35], [86], [87], [88]. Some security protocols are: Internet Protocol Security (IPsec), Transport Layer Security/Secure Sockets Layer (TLS/SSL), Datagram Transport Layer Security (DTLS), Secure Shell (SSH) Protocol or Secure Real-Time Transport Protocol (SRTP). These protocols have been used for microgrids security; however, for achieving a good level of security, the access of unauthorized nodes to the network information must be prohibited. A good option would be the use of MACsec [35]. A protocol that provides hop-by-hop security, so each node in the path has to verify the integrity and authenticity of the message in the reception block, and regenerate the MAC in the transmission block [35].

This stack of protocols for deploying decentralized smart microgrids networks is most often implemented through a MAS technology (Multi-Agent System). In fact, the IEEE Power Engineering Society Intelligent Systems Subcommittee created the group the IEEE Power and Energy Society Multi-Agent Systems Working Group (MASWG) for defining the correct use of the MAS technology within the distributed power grid domain.

MAS consists of multiple intelligent agents that interact to solve problems through cooperation, coordination and negotiation. These agents can be structured forming fully decentralized topologies, where in each one of them the TCP/IP stack protocol is implemented to give them fully networking operation. Several papers have specially applied MASs to microgrids [89], [90], [39], [91]. However, the increasingly distributed and intelligent energy systems along with their multi-disciplinary nature yield such a big data volume that the management and control of microgrids is becoming a critical challenge. The latest research indicates that distributed MAS architectures have some limitations on the efficient and optimal management of these emerging microgrids [92], [93], [94], [95], [96] , which are described below:

1) MAS agents cannot simultaneously communicate with other agents, being only allowed one-on-one interactions among individual agents, i.e., the agents can only act as a client or as a server, which results in a lack of agent proactivity. In this way, if the agent detects a fault in its operation, it cannot communicate its fault to the network until another agent communicates with it. The absence of such functionality results in a poor microgrid critical resources management.

2) Agents individual behavior is easily to know, whereas that cannot be extended to the behavior of the whole system. To get the overall operation information about the microgrid dynamic network, clusters of agents working in the same microgrid application or with the same needs should be formed. The absence of such functionality might result in the lack of knowledge about the global status of the microgrid and, thus, in the sub-optimal resources allocation.

3) Agents have neither dynamic reorganization nor self-healing capabilities by themselves, which prevent to adapt to local-failures, microgrid blackouts, agents crashes or communication failures.

To overcome those limitations, a new generation of communication networks for microgrids is required. The new characteristics of those new networks are: i) Information exchange with neighboring DER management structures through virtual layers that allow dynamic reorganization, ii) Dynamic Reconfiguration and self-healing of DER management structures, iii) Better communication technologies for the proactive operation of devices and active consumers, and iv) New software layers at the TCP/IP protocol stack to meet the increasing microgrid service and complexity demands. These requirements are fulfilled by the new Peer-to-Peer (P2P) paradigm. Recent research suggests Peer-to-Peer (P2P) communication networks for microgrid environments which will give rise to the new dynamic distributed microgrids generation [97], [98], [99], [100], [101]. This argument is fully elaborated in the next section, as well as an implementation guideline.

5. FUTURE TRENDS FOR DYNAMIC MICROGRIDS

In spite of the progress discussed in the above sections, continued efforts are needed to address some issues associated with MAS decentralized communications on microgrids. A dynamic and complex system like a microgrid needs to be designed to adapt autonomously. P2P-based technology for distributed self-management could change the future of power grids, because the P2P architecture has become a powerful control paradigm in a dynamic microgrid.

A P2P network is a communication architecture for decentralized systems. The agents, called peers, in contrast to MAS systems whose agents only can act as a server or a master, can act as both clients (masters) and servers simultaneously, which allows the agents to be proactive. Regarding P2P topology networks, the connectivity between nodes is essentially virtual, i.e. logical and structured topologies that are built on top of the physical networks [102] [Figure 7]. Peer nodes do not suffer from the inflexibility of MAS physical network topologies, since they are logical in nature. Their increased flexibility allows for extensibility, self-healing and dynamic reconfiguration. This implies that peers communicate with each other to establish dynamic self-organizing structures on top of the underlying physical networks. The fact that P2P overlays can be built dynamically allows them to support a huge variety of application level services [103]. In addition, these structures can be deployed over wired or wireless communications technologies. Routing can be achieved with direct point-to-point LAN communications without sacrificing the self-configuration, scalability and fault tolerance properties of a P2P overlay [104]. However, P2P overlay networks are ad-hoc in nature [105]. The nodes are connected by multi-hop wireless paths using technologies such as Zigbee/IEEE 802.15.4, Bluetooth/IEEE 802.15.1 and IEEE 802.11.

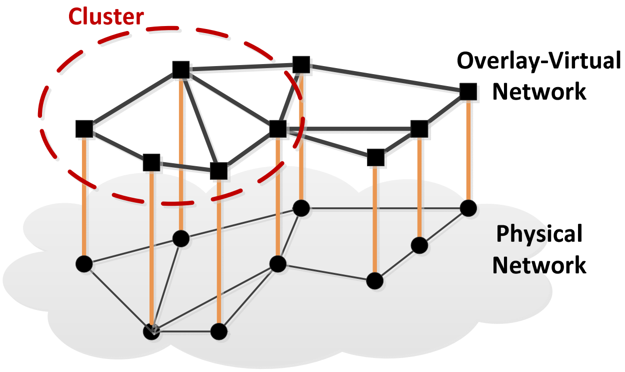


Fig.7. Overlay Network Architecture Scheme

Due to the virtual layer of the P2P architectures, peers disconnection from their underlying physical layer is allowed. This means that creation of a group of peers (clusters) for doing a particular task on a microgrid is possible [106]. Examples of clustering objectives include energy balancing, islanding and blackout prevention [37].

Therefore, virtual self-management allows agents to make local adaptive decisions on the basis of the information they receive from the agents to which they are linked [107], i.e., global goals are achieved by local management on the basis of local goals and knowledge. In this context, the holonic system approach has emerged [37], [108], [109]. This concept balances the importance of global and local objectives through a hierarchy of collaborative holons. The word holon is composed by "holos" meaning whole and the suffix "on" which implies particle or part, so holon=whole & part. Thus, the term comes from a recognition that any peer is simultaneously a whole entity comprised of sub-entities which interact to form different types of holarchy (based in P2P). Besides peers can find one another based on peers-IDs or peers attributes among the peers multitude. Thus, the responses to objects cached in the local overlay contain pointers to nodes that are close to the node issuing the query, thus reducing congestion on the network as well as network latencies [110].

Concerning mechanisms and protocols, the TCP/IP stack protocol is the most suitable standard for developing the peers. However, the overlays services need an additional software layer on the top of the TCP layer. Figure 8 presents a layered view about the different communication architectures for microgrids evolution.

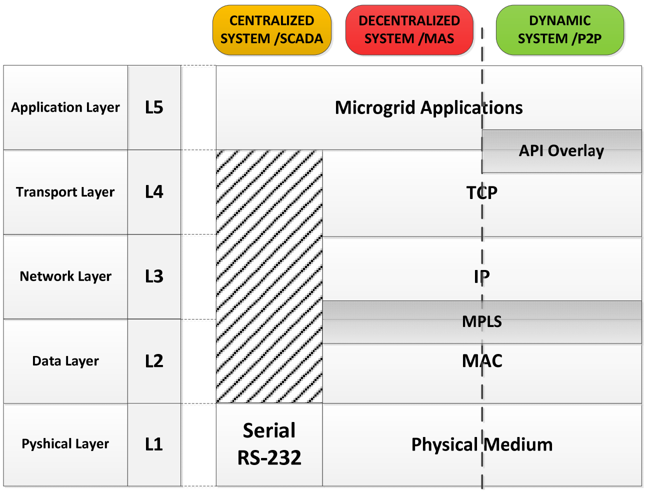


Fig.8. Protocol stack microgrid system evolution

The API Overlay layer is used to provide overlay-P2P services, being normally composed by two software layers: Overlay Routing and Messaging Layer and Overlay Management Layer (See Figure 9). Here, Software Defined Networking (SDN) is a need to virtualize networks.

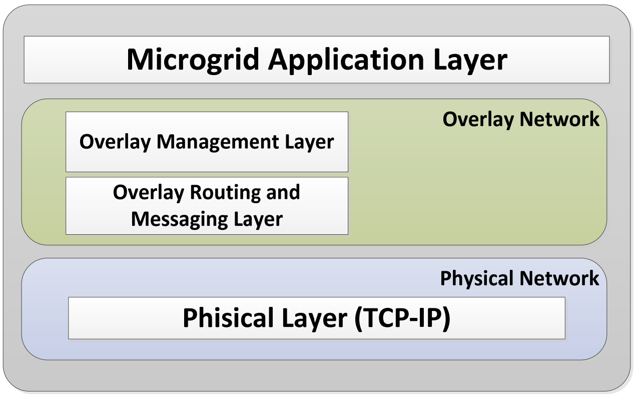


Fig.9. Stack Protocol of P2P Overlays

Overlay Routing and Messaging Layer provides networking P2P services to achieve the resource and network discovery, session establishment, routing, data transfer between nodes and entry/exit management of nodes (Plug and Play). The second application layer working on P2P service is responsible for the processing and data analysis, event management and status supervisory microgrid for stability maintenance.

As a result, it can conclude that this approach differs from conventional MAS in the dynamic and flexible cooperation, competition, supervision and part-whole. In addition, overlay structures combine the advantages of distributed control (such as scalability, adaptability and resiliency) and centralized control (reliability, optimally, practicability). Nevertheless, these P2P networks are still at the preliminary study stage for their implementation on the microgrid environment, being more research needed. Due to the growing complexity and unpredictability of the electrical systems, the study of microgrid dynamics becomes more complicated and new challenges arise which need to be addressed, such as:

- Peer-to-peer networks are mainly developed for file and processor cycle sharing, whose network performance requirements are less critical [111]. Thus, adapt this network technology to the performance networking smart microgrid requirements is essential. In this regard, it is needed to extend IEC 61850 standard in order to include this decentralized control and interoperability [83], [84].

- The current microgrid applications are not able to manage the uncertainty variability of distributed energy resources, among other factors that can change over time, because the methods used are often based on linear models and deterministic forecasts that do not adequately manage the dynamic behavior of microgrids [112]. For this reason, advanced stochastic algorithms, predictive analytics and the use of nonlinear schemes should be applied into future microgrid applications to produce results with higher fidelity [113], [114], [115].

- The increasing number of renewable energy sources and microgeneration as well as the integration of a large amount of DER units in the microgrid requires advances in high performance computing and parallel processing. Due to get that, these methods require, on one side, greater quantities and greater speed in the data flow. On the other side, reduced processing data time and results in a more sensitive time scheme [116], [117]. Therefore, data compatibility and exchange are likely to emerge as major challenges for implementation of dynamic microgrid capabilities.

- Currently, the data repository implemented in microgrid system use different forms of data; they can be structured and unstructured data. The development of a universally compatible communications protocol to handle these diverse data forms is another challenge to carry out [118].

Overall, the improvements in microgrid control systems for the future advanced microgrid generation are focused on leveraging fundamental advances in communications, mathematics and software computation as well as enable better technologies needed to increase the ranges and applications of energy-efficient advanced microgrids [118]. Figure 10 shows a possible evolution path towards dynamic microgrids. The comparison criteria and results can be found in table 4.

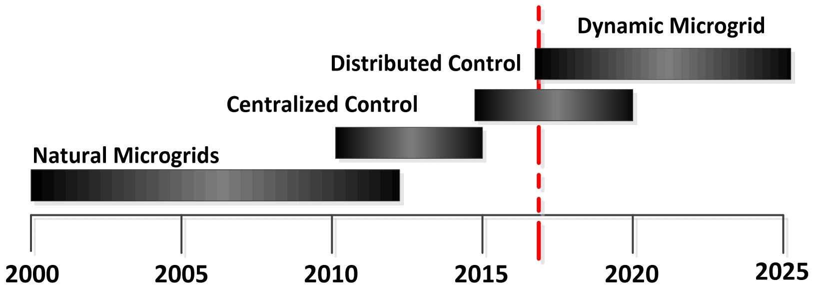


Fig.10. Roadmap to evolving to the dynamic microgrid.

	CENTRALIZED (SCADA)	DECENTRALIZED (MAS)	DYNAMIC DISTRIBUTED (P2P-Overlays)
Access of information	Status microgrid information through the whole units	MAS provides each independent control with information about its neighbor	Control about neighbor or cluster knowledge
Data communication Structure	Global & synchronous communication	Local & asynchronous communication	Local & Global & asynchronous communication
Real-Time Functions	Difficult and expensive	Possible and inexpensive	Easy and inexpensive
Plug & Play Capacity	MGCC must be programmed	Can be achieved without any modification of the controller	Inherent to peers
Grid Model	Global grid model	Local grid model	Local and Global grid model
Fault Tolerance Ability	Poor fault tolerance ability	1 router failure → tolerated n routers failure → costly	n routers failure → tolerated self-healing
Flexibility &Modularity	Reconnection is required for additional DERs	MAS can install modular and scalable systems	Nodes can exit and enter without changes in the network
Scale	Few nodes	IPv4 →2^{32} nodes IPv6 →2^{128} nodes Hierarchical Domain	>2^{128} nodes Names Domain
Destination Nodes	Node identification not allowed	Unique IP identification → node	GUID (Global Unique Identifier) → several host nodes (Routing at nearest)
Interoperability	Not possible	Possible	Demanding
Network Performance	High Latencies and low bandwidth. QoS not allowed	Greater latencies and bandwidths. QoS is allowed	Low latencies and high bandwidth. Inherent QoS
Network	Physical (EPA)	Physical (TCP/IP)	Virtual (o TCP/IP)
Security	Poor	Only where all nodes are reliable	Reachable, even in unreliable environments
Anonymity	Not possible	Not possible	To a limited extent

Table 4. Microgrid evolution system comparison

6. CONCLUSIONS

This paper has reviewed the evolution of microgrid communication systems, from those in initial microgrids to the emerging distributed systems. Recent research trends have been also discussed. This paper highlights that network communications in microgrids have more critical performance requirements than other IT systems due to the need for higher reliability, scalability, robustness, QoS and cybersecurity. The constraints of current microgrid communication systems, produced by the penetration growth of distributed energy resources, have been identified.

The research conducted up to date has produced important advances in communications achieving a decentralized and adaptable microgrid, having established a significant basis for the future deployment of new microgrids. It has been shown that intelligent, autonomous and communicative entities can lead to the successfully control of an energy system. The adoption of the TCP/IP stack protocol allows end to end communications and network interoperability.

Improvements of the network topology to best fit dynamic and flexible environments have been described. However, research is still required towards the next generation of dynamic microgrids, where DERs are widely coupled into the energy systems and should be dynamically interoperated by means of ICT technologies.

The technical studies reported in the literature indicate that a new peer-to-peer communication system approach is required to support the transition from the current decentralized communication systems to the next microgrid generation. This argument is reinforced by the concept of holonic systems, which combine global and local objectives. A hierarchy of clusters (or holons) based on P2P is proposed in order to optimize the overall microgrid system performance.

Summing up, there are challenges and important open research issues that have been identified and discussed, whose main purpose is to enhance the performance of peer-to-peer communication networks for their operation on microgrids. Adaptive logic and stochastic software approaches can be used for reaching the goals.

NOMENCLATURE

CIM	Communication Information Model
DCCP	Data Congestion Control Protocol
DCHP	Dynamic Host Configuration Protocol
DER	Distributed Energy Resources
DG	Distributed Generation
Diffserv	Differentiation Services
DMS	Distribution Management System
DNO	Distribution Network Operator
DNP3	Distributed Network Protocol 3
DNS	Domain Name Service
DTLS	Datagram Transport Layer Security
EPA	Enhanced Performance Architecture
GOOSE	Generic Object Oriented Substations Events
GUID	Global Unique Identifier
HSPA	High Speed Packet Access
ICT	Information and Communication Technologies
IED	Intelligent Electronic Device
Intserv	Integrated Services
IP	Internet Protocol
IPsec	Internet Protocol Security
ISO/OSI	International Standards Organization/ Open Systems Interconnect
LC	Load Control
LTE	Long Term Evolution
MAC	Media Access Control
MACsec	Media Access Control Security

MANET	Mobile Ad-hoc Network
MAP	Mesh Access Point
MAS	Multi Agent System
MG	Microgrid
MGCC	Microgrid Central Controller
MMS	Manufacture Message Specification
MO	Market Operator
MPTCP	Multi Path Transport Control Protocol
MS	Micro Source
NAT	Network Access Translation
NTP	Name Time Protocol
OFDM	Orthogonal Frequency Division Multiplexing
P2P	Peer-to-Peer
PCC	Point of Common Coupling
PLC	Power Line Carrier
PPP	Point-to-Point Protocol
QoS	Quality of Service
RF-mesh	Radio Frequency mesh
RLC	Radio Link Control
RTMP	Real Time Measurement Parameters
SCADA	Supervisory Control and Data Acquisition
SCTP	Stream Control Transport Protocol
SDH	Synchronous Digital Hierarchy
SDN	Software Defined Networking
SMG	Smart Microgrid
SMV	Sampled Measured Values
SNTP	Simple Network Time Protocol
SONET	Synchronous Optical Network
SS	Storage System
SSL	Security Socket Layer
SSTP	Scalable Secure Transport Protocol
TCP	Transport Control Protocol
TDM	Time Division Multiplexing
TLS	Transport Layer Security
ToS	Type of Service
UDP	User Datagram Protocol
WDM	Wave Division Multiplexing
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WMN	Wireless Mesh Network
WPAN	Wireless Personal Area Network
WWAN	Wireless Metropolitan Area Network

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