Communication Improvements for Intelligent Systems in Microgrids - Part I

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***Abstract*—Microgrids are small-scale electric power systems that emerge as an alternative to solve the current problems of conventional networks and transportation. The main objectives that they pursue are the reliability, diversification of energy resources, reduction of carbon emissions, reduction of costs and the introduction of intelligent control techniques, which increase dependence on communication networks. Some research related to communications in electrical networks and transportation has been developed, but few are related to the appropriate communication system, according to the intelligent control algorithm. This paper proposes the best architecture for intelligent microgrid applications based on latency, QoS, bandwidth and capital cost, to improve control and operation. In addition, the fundamentals of communications and control strategies for intelligent microgrids and electric vehicles are described. The results show that communication technology affects the performance of control applications and the smartness of the grid, which causes poor quality of service.**

Keywords*—*Microgrid; Communications; Intelligent Systems; QoS, capital cost

I. Introduction

With advances in information technology and communications, most industrial sectors have been revolutionized. In contrast, power grids still operate under the same principles of the last century. The energy demands in our societies require a more reliable, secure and cost-effective network [1]. As presented in [2], only in the United States in 2010 the electric power and transport sector accounted for 68% of total energy consumption. Also, the carbon dioxide emissions by the transportation and electric power sector were 1881 and 2271 million metric tons, respectively [3]. Microgrids (MG) are small active distribution systems formed by distributed energy resources (DERs), storage and loads. Its most attractive properties are the ability to operate off-grid in case of failures and the possibility to feed the excess of energy generated by the consumers to reduce their costs. On the other hand, MG is characterized by a high penetration of renewable energies and intelligent applications, increasing the complexity of the system. A typical structure of MG is showed in Fig. 1, where the microgrid central controller (MGCC) is a main controllable unit within the system. Also, a microgrid controller (MC) is responsable for frequency and voltage regulation and load controllers (LC) could be either microgrid source controllers or load controllers. Recent research on intelligent systems to increase the efficiency of the electrical network has grown due to the high information volume and the need to optimize the generation of electricity. For this reason, a flexible communication infrastructure is necessary to support a high number of intelligent devices. Based on the concept of microgrids which integrates distributed generation, several technical problems can be resolved in a decentralized way, reducing the extremely complex tasks in the central controller. [4]. Due to MGs characteristics of increased penetration of renewable sources, self-sustainability, fault tolerance, reliability, security and scalability; intelligent control algorithms are required to be fully integrated with standard power management mechanisms. These algorithms [5]–[7] should be capable of processing information intelligently and making real-time automated decisions. An alternative to introduce more intelligence in the power grid is to add smart systems combined with control techniques, distribution network and communications, during normal or outage operation. The algorithms applied to microgrids optimization present different critical requirements such as latency, the volume of data, or computational cost. Currently, almost all communication systems and protocols in microgrids have been developed for computer networks, telephony, or commercial devices on Internet (e.g., TCP/IP, HTTP, SMTP). As a guarantee to the proper functioning of the control systems, it is necessary to have an efficient communication architecture that allows good performance of the intelligent applications.

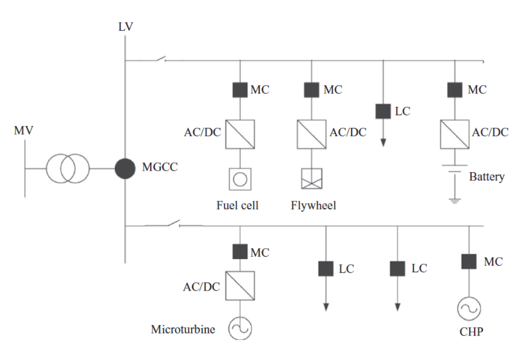

Fig. 1: Typical microgrid structure in medium voltage (MV) and low voltage (LV) [6] .

Some of these communication systems are already installed without the possibility to make modifications, due to economical aspects or by the field conditions. For this reason, it is necessary to adjust the proposed architecture before applying an artificial intelligence technique, to ensure the development of the algorithm and considering all requirements. The decision to choose an intelligent system, to solve a certain optimization problem, varies according to multiple elements. Some of this are network topology, the type of data or the volume of information, computational and time requirements and the minimum error rate allowed. In this research work, we survey the main intelligent systems (IS) applied to microgrid control and the possible communication technologies associated. In addition, we propose the suitable communication technology to apply different machine learning algorithms for MG infrastructures, to improve control operation at maximum energy efficiency, less latency, bandwidth, and capital cost. It also outlines the fundamentals of communications and control strategies for deploying intelligent microgrids, communications for IS challenges and future research directions.

II. Basic concepts about control and intelligent systems on microgrids

The control and coordination of each element of the DERs must be supervised periodically. Some of the most important challenges in microgrid control and protection are: bidirectional power flows, stability issues, modeling, low inertia, uncertainty, output control, power balance and economic dispatch [4]. The most common alternative to perform control in the MG is to use a centralized architecture, where in a central node all decisions are made and control techniques are applied. This proposal has the drawback that a failure in this node may interrupt the service. Hence, new techniques are being studied to develop decentralized architectures, which increases the communication systems complexity and their communication requirements. The centralized scenario is characterized by sending and receiving control commands from the central node. In addition, the initial phase has lower implementation costs, although the communication must increase the coverage area. On the other hand, communications delays are higher and there is less network reliability. This type of control is acceptable when the microgrid is small, or when the costumers have similar goals. The distributed alternative consists of clustering the centralized scenario into smaller communication zones according to distributed generators, storage devices and controllable loads. Each of these zones has its own control center, which is supervised by the highest central controller (MGCC). From simulations, in [8] authors show that the costs of implementing a centralized and a decentralized infrastructure are similar. In this study, they conclude that decentralized control improves latency and reliability. For this reason, decentralized control is generally used in large microgrids with a high number of devices, for real-time monitoring or when we need adjust different parameters. One element that allows the development of decentralized control systems has been the use of intelligent applications.

A. *Intelligent systems applied to microgrid*

The fundamental objective of power generation is to optimize the cost, distribution and demand, as well as to maximize the benefits. This section addresses different optimization approaches to minimize losses, reduce costs and guarantee availability or reliability. The most important IS techniques for optimization applied to microgrids can be grouped as population-based-metaheuristic, fuzzy systems, artificial neural networks, multiagent systems, game theory and hybrid systems. To minimize energy costs, some researchers have been using convex optimization, stochastic optimization and particle swarm optimization (PSO) [9]. Also, linear programming (LP) was used to minimize energy costs in [10], and a multi-objective optimization model for annual cost was presented in [5]. Investigations within population-based-metaheuristics as PSO [11], or artificial bee colony (ABC) [12] show the possibility to solve the optimal power flow with photo-voltaic (PV) panels, wind turbines and diesel generators. Game theory is one of the most common methods to solve energy management problems. The backward induction method [13] is used to solve a three-stage non-cooperative game problem. Also, in [13] a hierarchical game was established according to the interaction between the energy provider and the consumers. The literature shows that communication systems in the MG present some drawbacks that could not been solved. The tendency to use distributed control techniques and the integration of several DERs, produces new challenges in the field of communications [14]. Networks designed to connect these scenarios must be able to provide services when network traffic is high. To add more intelligence to the grid, the architecture must be robust and fail-proof, with the possibility of making decisions without the human intervention.

B. *Intelligent systems for transportation in MG*

The transportation systems that we know, were developed for many years ago. In these systems, each vehicle works independently, making global usage difficult. Currently, these systems are increasing and named intelligent transportation systems (ITS), which includes several types of communication, allowing global routes, interurban railway networks, maximizes the utilization of the vehicles and reduce the costs. An alternative to solve some of the problems of electrical networks and transportation may be the integration of microgrids and electric vehicles (EV). In this way, the term vehicle to grid (V2G) emerges, which takes advantage of the energy storage systems of EV to provide energy to the power grid.

The effectiveness of an electric vehicle lies in its control strategy. For this reason, numerous techniques have been developed from intelligent algorithms to perform the control of the elements that form EV. For example, fuzzy logic has been used to control the non-linear behavior of power trains [15] and to determine the torque split between the internal combustion engine and the electric motor [16]. Also, fuzzy logic was presented in [17], as a control speed in EV, to improve the stability under different road constraints condition. To predict the next state in this research, fuzzy logic is combined with the GPS communications system and a new control logic is presented from these elements. Another optimization algorithm with specific requirements from the point of view of communications is presented in [18]. In this research, PSO is used to regulate the frequency, manage the battery charge and help users to define their routes through a framework. The communications in this system are made through dedicated protocols in the network infrastructure that is defined or through the internet. An overview of different communication methods applicable to EV is presented in [19]. Technologies such as Power Line Carriers (PLC), IEEE 802.15.4 (Zigbee), ZWave, and cellular networks were summarized. In addition, the authors conclude that broadband over power line (BPL), Zigbee, ZWave, and cellular networks, have sufficient throughput to relay IP data between EVs and the utility network. In contrast, when the control uses algorithms that are affected by latency, some of these alternatives are not sufficient and another communication technique is required.

III. Critical Communications Issues for Intelligent Applications

As a result of new control techniques and a high number of connected devices, microgrids must be sufficiently flexible to add or remove elements from the network, without affecting the performance. Research [20], [21] suggest that the availability of smart applications is around 99%, while for microgrids it should be 99.99%. Table I shows the critical aspects and traffic characteristic for communication requirements in MG scenarios. The real-time measurement function (RTMP) is necessary to control the parameters of the microgrid. It is essential to address issues related to the bandwidth, latency or error rate, on each RTMP [22]. According to system response, each RTMP function has its own parameters. For example, Table II shows the most important critical communication requirements presented by the international electrotechnical commission (IEC 61850) and the IEEE 1646 standard. These standards determine the most critical requirements of communication systems in power networks. All parameters in Table II must be analyzed carefully because they can affect the performance of the network and in the worst case suspend the service. Low bandwidth in applications with high data rates, could lead to bottlenecks, packet loss or distortion. Also, the delay can leave the actuator devices connected during failures, compromising the entire system. Several scientific groups are promoting research related to microgrids, their control and the use of intelligent applications in electrical systems. In contrast, communications based on intelligent applications still present challenges that need to be addressed, like: i) increase the performance of the network based on parameters such as QoS (quality of service), bandwidth or latency, ii) guarantee reliability of the system formed by different DERs and DG, iii) and cyber security problems. When the communication network begins to discard packets, the transmission error increases, the buffers start to run without memory and the network becomes unstable. A possible solution to the problem of congestion and packet loss is QoS.

TABLE I: Communication requirements for a MG [21]. AMR (Automatic Meter Reading), AMI (Advanced Metering Infrastructure), DR (Demand Response), and Electric Vehicle (EV).

Application	**Traffic characteristics**	**Critical aspects**
AMR/AMI/DR	Delay tolerant Mostly periodic/event based Small burst size Multicast/broadcast	Large number of devices High overheads High random access loads Uplink biased
DER/MG/EV	Delay sensitive Semi-periodic/event based Multicast/broadcast	Real-time communication High reliability Mobility (EV roaming)
Substation automation	Extremely delay sensitive No retransmission Event based Reliable multicast	Mission critical End-to-end delay bound High reliability
Wide area monitoring	Delay sensitive Periodic Limited retransmission	Continuous transmission Dedicated bandwidth High reliability
Distribution supervision	Delay sensitive/tolerant Periodic/event based/ random Low power consumption	Large number of devices Clustered sensor networks Data aggregation

TABLE II: MG critical requirements defined by IEC 61850 and IEEE 1646 standards.

Application	**Bandwidth**	**Latency**
Demand response (DR)	14-100 Kbps	500 ms-minutes
DERs and storage	9.6-56 Kbps	20 ms-15 s
DMS	9.6-100 Kbps	100 ms-2 s
AMI	10-100 Kbps/node	2000 ms
Transmission line monitoring	9.6-56 Kbps	15-200 ms
Substation automation	9.6-56 Kbps	15-200 ms
Home communication	9.6-56 Kbps	2-15 s
Fault location & restortation	9.6-100 Kbps	1-10 ms
Outage management	56 Kbps	2000 ms
Emergency response	40-250 Kbps	500 ms
SCADA	56-100 Kbps	2-5 s
Vehicle to grid (V2G)	9.6-56 Kbps	2 s-5 min

It allows a differentiated service according to the most critical applications, focused on a better use of bandwidth and latency.

A. *QoS*

Quality of service refers to the ability to provide differentiated treatment to packages of certain critical applications within the microgrid. In this environment, quality of service is used for distributed control and protection in applications that need to deliver information in the shortest time as possible. The analysis of the quality of service in the microgrids is generally based on the latency and packet loss. Some authors investigated the effect of quality of service in the distribution networks [23] and have been able to determine that WiMAX technology is the most convenient in terms of capacity of smart meters and QoS. To take advantage of the benefits of distributed control, several MG projects have connected some of their elements to the Internet [24]. However, the Internet is based on the best effort service, which gives the same preference for a control package and a measurement package, so QoS can not be guaranteed. The best communication protocol, associated technology and intelligent system depend on the balance between transmission rates versus reliability [25]. In the same way, security techniques must be increased to avoid intrusions or denial of service attacks.

IV. Communication technologies for IS

As a result of this paper, we find some important elements to take into account when we are developing efficient communication technology according to the requirements of IS. Some of them are described below and are based on [26]. Finally, we propose the appropriate technologies according to the optimization technique. Within the structure of a microgrid there are several elements that require communication technologies to provide the minimum QoS. Data aggregator unit (DAU) requires 3G, WiMAX or fiber optic interface towards the utility, and radio frequency mesh (RF), power line communication (PLC) or broadband PLC (BPLC) facing the last mile network [27]. Based on these possibilities and data rate requirements, it is decided to propose for connections between DAU and utility network, a technology with high bandwidth such as fiber-optics or WiMAX. Intelligent systems optimize MG applications through communication technologies, which provides the minimum requirements for the proper development of the intelligent algorithm. Fig. 2 shows this process in which the communication must be bidirectional, to guarantee greater reliability, lower latency and better results with the intelligent system. Applications within the advanced measurement infrastructure (AMI) require transmission speeds of 2-5 Mbits/second. Technologies such as fiber-optical, satellite or WiMAX can satisfy these needs, and provide the necessary security and support for new technologies. The communication standards IEEE 802.15.4 (ZigBee) and IEEE 802.11 (WiFi) are widely used to connect application servers with smart meters in homes, industries or smart buildings [28]. An analysis of packet loss and latency from LTE technology is developed in [29], while authors in [30] propose a new communication protocol for distributed applications (smart energy profile 2.0). The study of Internet protocols for the exchange information between external entities and service providers is proposed in [31]. For real-time pricing data, technologies such as IEEE 802.11 (WiFi) and 802.15.4 (Zigbee) can be deployed, while the power line communication PLC is mostly used in automated meter reading systems and islanding prevention. When passing the microgrid to work in islanded mode, it is expected that critical parameters such as latency, packet loss or data rate will be affected by the increase of control and configuration messages from intelligent applications. The technologies proposed according to these parameters are WiMAX or optical fiber. Control of DERs, fault isolation and overcurrent protection are some of the most critical tasks within communication systems in microgrids. These elements require very low latency, extremely high data rate and availability close to 100 %. For this reason, the most effective solution is to use optical fiber.

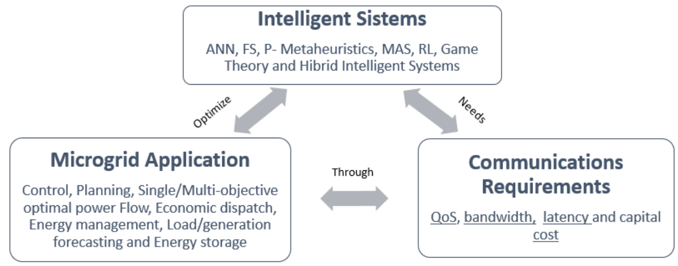

Fig. 2: Relationship between intelligent systems, applications and communication requirements.

According to the european telecommunications standards institute, synchronized phasor measurement units (PMUs) are connected through broadband (like optical fiber) for high voltage network [32]. On the other hand, in [33] a study of the best alternatives to communicate PMU and the phasor data collector (PDC) is carried out. This analysis determined that the best alternative was to use WiMAX technology. Communication between intelligent applications in the synchrophasors, technologies such as optical fiber, Ethernet, microwave and BPLC have been applied. The preferred technology is optical fiber due to its bandwidth, low electromagnetic interference and high data rates [34], [35]. In contrast, intelligent electronic devices IEDs operate in a local area network (LAN) environment and require dedicated connections such as Ethernet, WiFi, Zigbee or copper wire [36]. Due to the increase of the number of intelligent applications connected to the NAN-WAN segment, utilities are expected to achieve data rates above 500 Kbps [27], with low latency. With this constraint, most commonly used alternatives are WiMAX, microwave, and optical fiber. On the other hand, intelligent applications are also developed in the HAN environment, being the most common Ethernet, WiFi and ZigBee technologies. Important challenges when determining the type of technology results the compatibility with previous devices, the heterogeneity of manufacturers, transmission errors and the reduction of installation costs. Below are some of the future directions of this research.

V. Challenge and future research work

This section describes the future work of this research and the main challenges of communication technologies focused on control in intelligent applications.

- Intelligent applications in MG have critical requirements that need to be managed according to certain preferences such as those handled by the QoS concept. A differentiation according to the type of intelligent traffic, will allow best network performance.
- Develop a new transport protocol that allows to reduce the ETE delay between the connected devices.
- Prevent the attack on the system, detect intruders and protect the critical elements of the electrical network and the communication system.

TABLE III: Proposal of communication technologies for IS

CI Approach	Microgrid Application	Optimality	Technology proposed	Technology to avoid
Artificial Neural Networks (ANN)	Load/Generation Forecasting Fault Detection and Control	Optimal	HAN: DSL, WiFi, GSM WAN: Fiber optic, WiMAX	PLC, ZigBee or Satelite
Fuzzy Systems (FS)	Energy Management Energy Storage	High	HAN: DSL, WiFi, GSM WAN: Fiber optic, WiMAX	PLC or ZigBee
Population-based Metaheuristics	Planning Optimal Power Flow Economic Dispatch Energy Management	Optimal	HAN: WiFi WAN: Fiber optic, WiMAX	PLC, DSL, ZigBee or Satelite
Multi-Agent Systems	Energy Management Energy Storage Control	High	HAN: DSL, WiFi, GSM WAN: Fiber optic, WiMAX	PLC, ZigBee or Satelite
Evolutionary Algorithm (EA))	Energy Management Control	Average	HAN: DSL, Ethernet, WiFi, GSM WAN: Fiber optic, WiMAX	PLC, ZigBee or Satelite
Swarm Intelligence Algorithm (SWA)	Fault Detection	Average	HAN: WiFi WAN: Fiber optic, WiMAX	ZigBee or Satelite
Artificial Immune System (AIS)	Control	Near optimal	HAN: DSL, PLC, Ethernet, WiFi, GSM WAN: Fiber optic, WiMAX	ZigBee or Satelite
Reinforcement Learning (RL)	Energy Management Control	Medium	Practically any technology	Satelite
Game Theory	Energy Management	High	HAN: DSL, WiFi, GSM WAN: Fiber optic, WiMAX	PLC, ZigBee or Satelite
Hybrid Intelligent Systems	Optimal Power Flow Energy Management Planning Control	Optimal	HAN: WiFi WAN: Fiber optic, WiMAX	PLC, ZigBee or Satelite

- The growing use of intelligent applications, the increase in the number of renewable energy sources and the integration of DERs, require optimization algorithms and parallel processing. The compatibility and exchange of information, reducing the processing and delay are important challenges for the implementation of a dynamic MG.
- Improving technologies such as QoS for critical parameters is another element to consider.
- Simulate and compare the performance of each technology in the HAN, NAN and WAN scenarios, in order to evaluate the results of this paper with those of the simulation.

Apparently, according to literature the best candidate to ensure a robust, flexible, secure and economical communication, come from wireless technologies such as WiMAX or WiFi. The fundamental disadvantages are the reach of the devices and availability, so to increase these elements within the microgrid, another alternative can be implemented like LTE. On the other hand, optical fiber is an alternative to higher deployment costs and poor adaptability to environmental conditions, but its robustness, low interference, and bandwidth, providing an advantage over its competitors.

VI. Conclusion

This paper identifies the main restrictions presented by communication systems on the intelligent microgrid scenario. It was found that there are more critical requirements such as latency, transmission error or delay, which must be considered compared to a communication system of a computer network. Intelligent applications in NAN require high reliability and a low delay between devices. The same applications in WAN environments need very high reliability and security, as well as extremely low latencies. Even though there are publications that discuss the use of intelligent systems in microgrids, there are few papers that provide a delay sensitive and a reliable framework for the control of the grid as well as fewer papers that discuss QoS provisioning techniques to address and monitoring delay critical intelligent applications. The most effective technologies for IS are WiFi in the case of HAN communication due to its low cost, high flexibility and sufficient transmission speeds to avoid bottlenecks in intelligent applications. In the case of WAN, the most efficient technology will be optical fiber and WiMAX due to the large bandwidth, high immunity to noise and the possibility of modifying its QoS. The use of the TCP/IP allows interoperability between the different devices in the network. On the other hand, the design of the network based on intelligent applications must avoid technologies such as ZigBee, PLC, or satellite, due to the high latencies or the interference, which makes them unfeasible for IS. However, it is still necessary to investigate in future dynamic microgrid, where intelligent applications will be able to interact and adjust according to DERs, failure or control mechanisms without human intervention.

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