Filipe Bandeiras[1], Mário Gomes[1]*, Paulo Coelho[1], José Fernandes[1], Antonio Camacho[2], Miguel Castilla[2]

MICROGRID ARCHITECTURE EVALUATION FOR SMALL AND MEDIUM SIZE INDUSTRIES

[1]Instituto Politécnico de Tomar (IPT), Tomar, Portugal
[2]Department of Electronic Engineering, Technical University of Catalonia, Vilanova i la Geltrú, Spain
*Corresponding author, E-mail: mgomes@ipt.pt

Abstract: The content of this paper addresses possible approaches that will eventually allow the development of microgrids for small and medium size industries on a massive scale. Therefore, it addresses in a comprehensive way, the most suitable communication technologies for microgrids in this type of enterprises. Several energy sources that can be implemented in industrial microgrids are also briefly addressed, including generation and storage units frequently adopted for power supply in small scale distribution grids. The overview of communication technologies and energy sources takes into account the financial limitations of small enterprises with the purpose of assisting the study of industrial microgrid architectures. In addition, a case study is presented in order to observe how a centralized and a decentralized deployment of energy sources affect the performance of a small or medium scale industrial microgrid. Since this sector is very important for the development of modern societies, it should make use of the most advanced infrastructures in order to be more sustainable, both environmentally and competitively.

The practical limitations applied to industrial microgrids (e.g., lack of standards in the grid codes, some unfit technolo gical performance and amiss system design) shows that the subject presented in this paper deserves much more research and developments. Thus, this work demonstrates the importance of the development of the microgrid for the small and medium-sized enterprises sector.

Keywords: Industrial microgrids, centralized / decentralized architectures, communication technologies, renewable energy sources

1 Introduction

During the past decades there has been an important development in power systems as a result of an efficient planning and growth in innovation, which led to a considerable quality improvement to the supplied electricity. Nevertheless, the improved quality of the power system is not yet present in every location [1]. Isolated and remote locations still have a defective and faulty power grid with constant power outages. During a power outage of the public power grid, customers may have to wait for days before being reconnected to the grid and industries that operate with crucial loads cannot afford any power interruption. A failure in the industrial power supply may lead to significant technical problems, production and financial losses [2]. The environmental concerns associated with power generation from fossil fuels are encouraging industrial customers to look for alternative clean energy sources and energy efficiency measures. In contrast to large industrial enterprises, it may be difficult for smaller industries to adopt energy efficiency measures in order to reduce their carbon footprint and energy consumption. Most of them are unaware of energy efficiency improvements and cost-efficient applications of renewable energy resources. Lack of motivation and information, as well as no qualified personnel and limited financial conditions are the main barriers to implementing energy efficiency measures in small and medium size industries [3]. The energy efficiency improvements can go from simple no-cost and low-cost measures to large investments such as renewable energy sources (RES) and the integration of smart grids. The rules that govern the interaction between a microgrid (MG) and the distribution system operator (DSO) – grid codes – must be clear and effective [4]. Among others, the following two aspects: (i) there is currently no obligation for DSOs to grant MGs the right to reconnect after they have gone off-grid. In case of an industrial MG, this could lead to significant repercussions for an enterprise that could be potentially forced to cease production due to not being reconnected to the grid instantly after islanding, and (ii) the safety of maintenance engineers is a major challenge for electricity distribution networks. Grid codes require DSOs to know in real time whether MG cables are active or not to avoid accidents. DSOs and MGs must develop communication channels, and a protocol to ensure notifications are made in a timely manner. In both cases, the regulator needs to adapt the grid codes to ensure they are suitable for MG development.

An industrial MG is a practical application of the concepts of inverter-based MGs to the power supply of industrial processes [5, 6]. In this context, the principal requirement is the uninterrupted power supply of the priority loads [7]. Typically, the loads are electrical machines in charge of a continuous process in a production line. For instance, the manufacturing of paper or plastic film are two examples of a production line requiring reliable power delivery to avoid damaging materials during the production process. The possibility to operate the industrial MG in islanded mode is essential in this application to guarantee the continuous operation during unexpected power events and grid faults [8]. Other types of MGs have been studied in the literature including residential, commercial, institutional, military and remote MGs. They incorporate specific requirements such as variable profile high-power loads, physical and cyber security and forced islanded operation [6].

Literature sets the key steps for operating a MG in diverse types of facilities. Thus for small and medium-sized enterprises sector, the methodology to be adopted should follow two major fields (i) Current situation and (ii) Project feasibility [4]. In which (i) focus on the evaluation of the operational conditions in the facility according to the following steps: a) Technical setup (i.e., current/historic levels of power supply reliability, current power generation mix, type of distribution grid, typical load profile, identification of critical loads versus non-priority loads); b) Environmental considerations (i.e., emissions rates, emissions targets); c) Financial considerations (i.e., operating costs: fuel costs, electricity prices, fuel price volatility, opportunity costs of outages caused by historic levels of reliability); and d) Project objectives (i.e., minimize energy bills, reduce outages, reduce emissions, provide spinning reserve, peak demand reduction). Additionally, the evaluation of the major field (ii) emphasizes the following steps: a) Applicable policies (i.e., planning and permitting regulations, power tariff structure, grid connection charges, grid use of system charges); b) Renewable resource (i.e., wind speeds, solar irradiation, shadow effects); c) Site information (i.e., land availability, thresholds that trigger planning permission, environmental impact assessment, visual impact assessment, timescales for development, supply chain lead times); d) Commercial structures (i.e., self-ownership, infrastructure fund, returns to owners…); e) Financing structure (i.e., balance sheet, debt/equity ...); and f) Technical viability (i.e., grid integration principles, technology choices and optimum size, site layout, ability to feed power back to grid or not …).

This paper contributes with a study on the architecture for small and medium size industrial MGs and, in particular, it focus on the selection of the best approaches. To this end, a case study based on centralized and decentralized architectures has been carefully evaluated. Grid-connected and islanded operational scenarios has been considered for both architecture approaches and it was observed that for both scenarios a decentralized architecture provides better bus voltage profiles than a centralized architecture. This paper is organized as follows . Section 2 briefly explains the core of a MG. Section 3 performs the main characteristics of DER technologies with potential to be adopted in an industrial MG and their possible architectures. Section 4 presents the essential of communication architecture schemes and the proposed one in this paper. Section 5 presents a case study with centralized and decentralized MGs, including selected simulation results to validate the analysis. Section 6 presents the main conclusions.

2 Microgrid concept

A MG can be seen as an integration of microgeneration units, storage units and controllable loads located in a distribution grid that serves multiple economic, technical and environmental aims. It performs an efficient management and coordination of the available resources and it should be capable of handling both grid-connected and islanded operation modes [9]. When connected to the main power grid, the MG operates in grid-connected mode. When disconnected from the main power grid, due to an intentional or unintentional power interruption, the MG operates in islanded mode. In addition, the loads are categorized according to a priority. Crucial loads are set to high priority and must be supplied in all circumstances. Non-crucial loads are set to low priority and can be disconnected when the available energy is low [10]. A MG includes an electric power grid with distributed energy resources (DER), a communication network and control devices that ensure a safe and optimized grid operation. The MG central controller (MGCC) coordinates the local controllers, provides set points and controls their operation. Microsource controllers (MC) are local controllers responsible for controlling and monitoring the local generation and storage units. Load controllers (LC) are local controllers responsible for controlling and monitoring the local loads [9]. A brief diagram of an industrial MG is represented in Fig. 1.

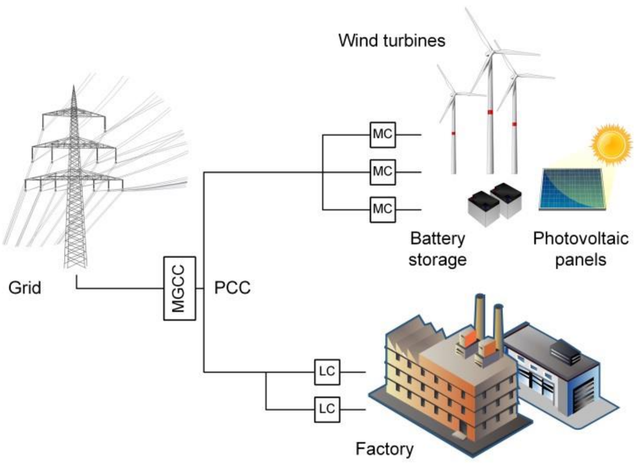

Fig. 1: Diagram of an industrial microgrid concept

3 Microgrid power architecture

The implementation of low-carbon energy sources into the power grid has been made in order to reduce greenhouse gas (GHG) emissions in the power sector. This environmental effort led to several MG architecture configurations with high penetration of RES [11]. The MG power architecture for small and medium size industries can be centralized or decentralized, as depicted in Fig. 2. Sections 3.1 and 3.2 present the main aspects of DER technologies commonly adopted in MGs.

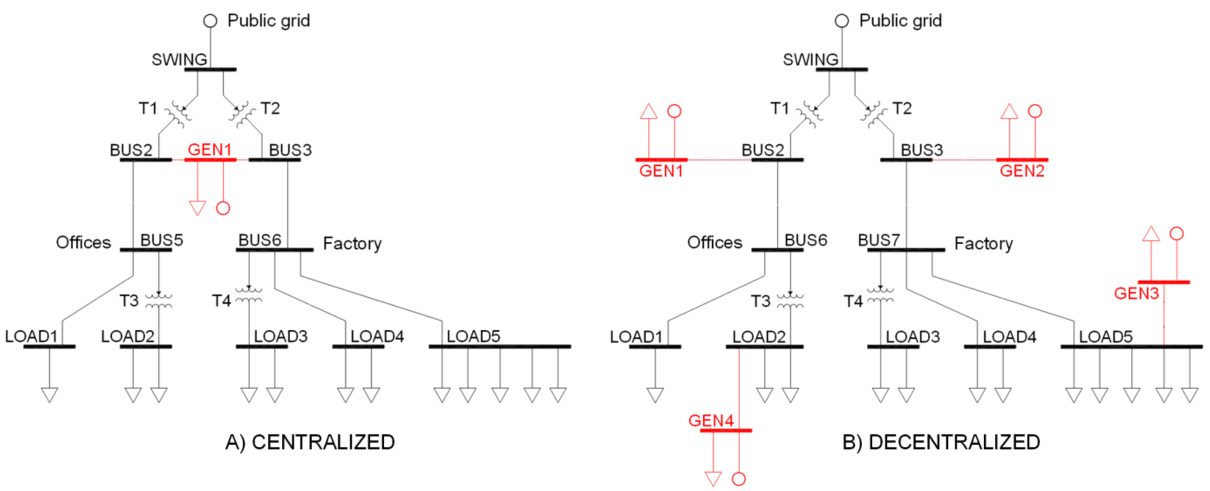

Fig. 2: Schematic of the industrial microgrid power architecture: A) centralized and B) decentralized

In order to assess what the most economically viable MG architecture should be, it is necessary to study the cost/benefit trade-off according to the company specifics. In a simple way, the best solution for small and medium size industries is the following one:

- Centralized architecture for companies with no wide areas of implementation (e.g., paper / pulp manufacturing, metal industries, assembly / repair industries, distilleries …).
- Decentralized architecture for companies occupying wide areas (e.g., agribusinesses, large sawmills …).

FALTA EXPLICAR EL PORQUE. AUNQUE SEA EN UN PAR DE LINEAS POR SOLUCIÓN

3.1 Distributed generation units

Distributed generation (DG) units can include photovoltaic (PV), wind turbines (WT), fuel cells (FC) and micro turbines (MT) [12, 13]. The DG units are located within the grid and aim to fulfil the local demand. Tab. 1 presents the characteristics of DER technologies commonly adopted in MGs.

A PV system converts solar energy into electrical energy by exciting electrons in silicon cells, making PV system an intermittent energy source. PV generation coincides with peak energy demand, and provides low maintenance and operation costs, as well as a long service life and positive environmental impact [14]. However, PV cell efficiency is low and power generation is dependent on location and weather conditions. Solar cells made from crystalline silicon (c-Si) are generally the most common and efficient ones. Depending on the alignment of the silicon molecules and manufacturing process, silicon cells can be called monocrystalline (mono-Si), polycrystalline (poly-Si) and thin-film amorphous (a-Si) cells. Including solar trackers in PV panels is a common adopted solution to maximize the production of the PV system. Solar tracker devices keep the PV panels oriented towards the sun throughout the day in order to minimize the angle of incidence [15].

A WT system converts wind energy into electrical energy by using the wind force to turn the blades and make a rotor spin, being also an intermittent energy source. The main parts of a WT are the rotor and the nacelle. The nacelle contains the brake, gearbox to increase rotational speed and the generator that is connected to the rotor by the main shaft. Depending on the rotor orientation, WTs can be classified in horizontal axis wind turbines (HAWT) or vertical axis wind turbines (VAWT).

A FC converts chemical energy from a fuel into electrical energy through a chemical reaction of positive charged hydrogen ions with an oxidizer [16]. It consists of two electrodes and an electrolyte that allows the particles to move between them, the positive electrode is called cathode and the negative is called anode.

Tab. 1: Characteristics of DER technologies

Technology		Efficiency	Power	Cost ($/kW)
	mono-Si	15 to 23%		2500 - 4800 (1 - 100 kW)
Photovoltaic [17, 18]	poly-Si	13 to 16%	up to 10 MW	1700 - 3300 (100 - 1000 kW)
	a-Si	5 to 10%		1300 - 2700 (1 - 10 MW)
	HAWT	20 to 50%		4000 - 10000 (1 - 100 kW)
Wind turbine	VAWT	20 to 40%	up to 10 MW	2300 - 5200 (100 - 1000 kW)
[17, 19, 20]				1500 - 3200 (1 - 10 MW)
	PEMFC	25 to 35%	up to 100 kW	1800 - 2000
Fuel cell	SOFC	50 to 60%	up to 200 kW	1500 - 1600
[21, 22]	MCFC	43 to 47%	300 kW to 3 MW	
	PAFC	40 to 42%	100 to 400 kW	4000 - 4500
Micro turbine [23]		25 to 30%	30 kW to 1 MW	500 - 3000
	Li-ion	75 to 90%	up to 50 MW	1200 - 4000
Battery storage	Pb-A	70 to 90%	up to 20 MW	300 - 600
[24, 25, 26]	Ni-based	72 to 78%	up to 50 MW	500 - 1500
Flywheel [25, 26, 27]		85 to 95%	up to 20 MW	200 - 600
Supercapacitor [25, 26, 27]		90 to 95%	up to 300 kW	100 - 500

The most common FC technologies for commercial and industrial applications are the proton exchange membrane fuel cells (PEMFC), solid oxide fuel cells (SOFC), molten carbonate fuel cells (MCFC) and phosphoric acid fuel cells

(PAFC). The FC technologies that operate at high temperatures can be used for combined heat and power (CHP) applications.
A MT produces heat and electricity from a combustion turbine. The basic components of a MT are the compressor-turbine package mounted on a shaft along with the generator and the recuperator that uses the turbine exhaust heat to preheat the compressed air. The exhaust heat can be recovered by the heat exchanger package and used in CHP applications. The MTs used for power generation can be recuperated or single cycle micro turbines. And depending on the shaft configuration, MT can also be classified as single shaft or split shaft micro turbines.

3.2 Energy storage units

Energy storage units can include battery storage (BS), flywheel (FW) systems and even supercapacitors (SC) [12, 26]. The storage elements are included to ensure an uninterrupted supply of power during outages and to set a power balance after significant changes in load demand [28]. Storage applications can be classified as centralized and decentralized units. Centralized units are normally installed at transformer substations serving power balance and frequency regulation aims. Decentralized units are normally dispersed over the whole grid, close to loads and generation sources, serving demand response aims. Clearly, in large grids the optimal location for dispersed energy storage units is close to loads in order to minimize power losses. This improves the bus voltage profile and might also prevent an oversized energy storage system. Considering the significant decrease in grid size, in MGs the location of energy storage units does not play an important role and is usually dependent on the area available for deployment. A BS system stores energy in chemical form and converts the stored chemical energy back to electricity when needed. A battery consists of an electrolyte and two electrodes, the cathode (positive electrode) and anode (negative electrode). In energy storage applications, a group of batteries is joined in parallel or in series, forming a battery bank to supply the local loads. Due to a high energy density, large amounts of energy can be stored in a battery. Most industrial energy storage applications are mainly focused on lithium ion (Li-ion), nickel metal hydride (NiMH) and lead acid (Pb-A) battery technologies. A FW system stores mechanical energy in a spinning shaft connected to a generator, the rotor spins building up kinetic energy and converts it to electricity when required. The rotor is suspended by magnetic bearings inside a vacuum enclosure to reduce friction. FWs are commonly adopted as power quality devices to smooth the transition between power sources and provide a supply of power during short power interruptions [25].
A SC bank stores energy in the form of electric field energy using series of supercapacitors. A SC consists of an electrolyte and two plates as electrodes separated by a thin insulator. The main advantage is the high power density, meaning that energy is stored and delivered relatively quickly. SCs cannot store a large amount of energy due to a low energy density, being mostly adopted to help power regulation in intermittent sources and to quickly compensate active and reactive power.
The development of energy storage technologies is another game-changer to leverage low-carbon MGs. Nowadays, lithium-ion batteries are the predominant storage technology for MGs. However flow batteries are also emerging. In order to assess what the most economically viable storage solution for a project should be, it is needed necessary to match the costs of storage with the company autonomy requirements.

4 Microgrid communication architecture

In order to monitor and control a system with integrated DERs, power converters and variant load patterns, an appropriated communication configuration has to be adopted. The configuration of the communication architecture depends on the existing grid design where the control devices are located, the number of DERs, and mainly on the communication technology chosen. The communication architecture can be implemented based on a centralized or decentralized approach. In a centralized approach (one-to-all), the central controller communicates with all the local controllers and coordinates their operation settings. The local controllers are simpler in this approach, since they are not in charge of making decisions. The central controller is responsible for making decisions based on the data received from the local controllers. This approach is fully dependent on a single central controller and a failure in this device can compromise the entire system, so in order to ensure its continuous operation redundancy may be necessary. In a decentralized approach (all-to-all), a central controller is discarded and each local controller uses data received from other controllers and coordinates the operation settings. In this approach, each local controller is in charge of processing data and making decisions, requiring more advanced and complex local control devices which increase the system cost [9]. The data can be transmitted through wired and wireless physical communication links. Generally, a wired communication network offers higher transmission speeds and is slightly more reliable and less susceptible to interference. Conversely, a wireless communication network includes lower installation costs and more flexibility to add new nodes to the existing network. Depending on the technology adopted, the communication system can also integrate both wired and wireless links in parallel to help reducing data traffic congestions in the wired links and improve the availability of the network [29].

4.1 Wireless communication links

There are several wireless technologies that are suitable for MG communication networks, such as Wi-Fi, WiMAX, Cellular 3G/4G, ZigBee and Bluetooth [30, 31]. Wi-Fi networks provide a flexible, reliable and high speed local wireless communication. Since these networks operate on the unlicensed spectrum, their deployment is relatively cheap. But at the same time, the use of a crowded unlicensed spectrum also makes them more susceptible to interference. WiMAX networks offer a long coverage area and high speed wireless communication. It provides good performance over long distances and supports thousands of simultaneous users. However, these networks require a complex management. A ZigBee network provides a low power and low cost local wireless communication. It is considered an ideal network for energy metering and management applications that require both low power consumption and low bandwidth with a low deployment cost [32]. A Bluetooth network also provides a low power local wireless communication with low deployment costs. It offers less latency than ZigBee or Wi-Fi networks and can be often used in local monitoring applications [30, 33]. Due to the limited range, both Bluetooth and ZigBee networks are unable to scale to large networks [31]. The 3rd Generation (3G) and 4th Generation (4G) cellular networks provide long distance wireless communications. The low power consumption of terminal equipment and an extensive data coverage area with high flexibility are the main advantages of cellular networks [31]. Furthermore, public cellular networks are already deployed and can be used with no maintenance costs [30]. However, there are high costs associated with the use of a service provider network and there is no guarantee of service during abnormal weather conditions [32]. Taking into account financial considerations, ZigBee and Bluetooth networks are the most economical wireless solutions available and might be the preferred choices for small/medium enterprises due to low power consumption and low equipment costs. Given their limited coverage area, these networks can be an ideal solution to enable data transmission between the respective controllers, sensors and meters in small scale grids.

4.2 Wired communication links

The MG communication network may also be integrated with physical wired communication links such as PLC, DSL and optical fiber [31, 34]. Power line communications (PLC) makes use of existing power lines for data communication. A PLC network provides a cost-effective solution with a low maintenance requirement [31]. Since PLC makes use of a single infrastructure for both data and power transmission and thus decreasing the cost of installation, this communication technology is the preferred solution for metering data transmission and the simplest to implement in smart grid applications. However, the noisy and harsh nature of the power line channel affects the data transmission and may decrease the signal quality [32]. An optical fiber infrastructure provides long distance communication with high data rates and robustness against radio and electromagnetic interferences. However, optical fiber applications are characterized by high installation costs, high terminal equipment costs and difficulty to upgrade. These disadvantages prevent optical fiber communications from being widely adopted in smart grids [31]. Active optical network (AON) requires electrically powered switching equipment such as routers or a switch aggregator to manage signal distribution and direct signals to the correct destination. A passive optical network (PON) does not require electrically powered switching equipment, instead it uses optical splitters to separate and collect the signals. Digital subscriber lines (DSL) use telephone line infrastructures to transmit digital data. This avoids additional communication infrastructures when a telephone line infrastructure is already deployed [31]. In order to use DSL networks, a communication fee must be paid to the telecommunication operator and the network needs to be regularly maintained [32]. Among the wired communication technologies available, PLC and DSL networks might be the best wired solutions for small/medium industries due to a cheap and simple implementation. In addition, most of the wired smart meter systems use PLC connections for data exchange.

4.3 Proposed communication network

The control system is a key element in the operation and performance of MGs. In this application, the control system is organized in a central controller responsible to perform the energy management of the MG and in local controllers in charge of the power processing of the inverters. In this case, the control system uses a centralized communication network as depicted in Fig. 3.

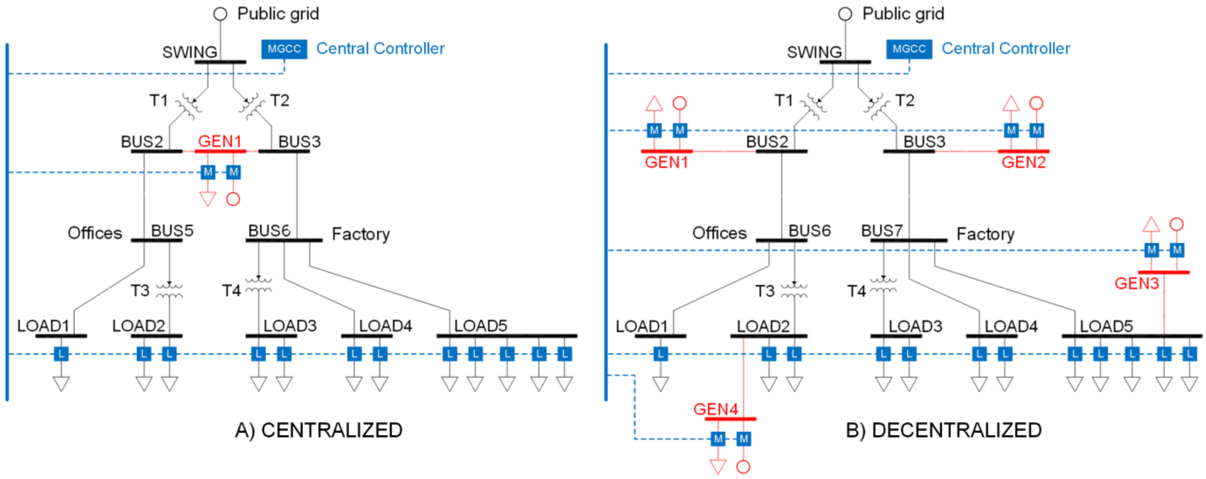

Fig. 3: Schematic of the communication network proposed for both industrial microgrid power architectures: A) centralized and B) decentralized

This network includes a MGCC located at the distribution substation that communicates with the respective local controllers. The MCs and LCs are represented with the letters M and L, respectively. The central controller can be a programmable logic controller device or a station computer to run SCADA software. Most of the hardware for MCs and LCs consists of intelligent electronic devices (IED) and remote terminal units (RTU) for supervisory control and protection applications based on data acquired from sensors and meters. Since the scale of the network shown in Fig. 3 is relatively small, the communication between the devices is achieved via DSL using twisted pair cables. This is an economically attractive solution and frequently used in residential and industrial applications. In this case, shielded twisted pair (STP) cabling might be the preferred choice over the cheaper unshielded twisted pair (UTP) counterpart, because it offers higher protection against electromagnetic interference of the factory setting under study.
In order to ensure an increased robustness of the microgrid to failures, we suggest the possibility of having redundant systems, namely at the communications level. For faults occurrences in twisted pair cables, we suggest, for example, the use of PLC, cellular, and in some situations Wi-Fi, Bluetooth or ZigBee. The choice must always ensure the security of communications.

5 Case study

This section presents a case study of an industrial MG with centralized and decentralized architecture, as represented in Fig. 3. The industrial MG developed for this study is based on data presented in [35]. The purpose of this section is to observe how a centralized and a decentralized deployment of DERs affect the performance of a small/medium scale industrial MG. The industrial site under study is a small factory that produces paper sheets. It contains a main factory and offices with a nominal power consumption of 320 kW and 80 kW, respectively. There are four step-down transformers inside the MG, transformers T1 and T2 are responsible for decreasing the voltage from 13.8 kV to 480 V, and T3 and T4 decrease the voltage from 480 V to 208 V in order to supply loads such as lights and office equipment. The factory building contains five induction motors, two air conditioning units, an elevator and lights. The office building contains an air conditioning unit, lights and office equipment such as personal computers, printers and fax machines. The data for each transformer and load is listed in tables 2 and 3.
During islanded mode operation, the power generator that simulates the public grid is disconnected from the MG at the point of common coupling (PCC). Given the intermittent nature of some generation units and the limited duration of power supply from energy storage units, loads cannot be continuously supplied for a long period of time. Thus, it is necessary to expand the operation time of the MG and ensure the system balance by prioritizing some of the loads

through a load-shedding schedule [36]. The study in [37] presents an approach to maximize the duration of power supply according to the amount of generated and stored energy in islanded mode. Consequently, all the loads in this MG follow a priority according to how important they are to the industrial process.

Tab. 2: Transformer data

Transformer	Primary (kV)	Secondary (kV)	Load (kW)	Rating (kVA)
T1	13.8	0.480	80	200
T2	13.8	0.480	320	1000
T3	0.480	0.208	65	200
T4	0.480	0.208	10	40

Tab. 3: Load data

Load	Voltage (V)	Unit size (kW)	Power factor
Induction motor	480	50	0.8
Office equipment	208	12.5	0.96
Air conditioning	480	15	0.95
Elevator	480	30	0.97
Light (factory)	208	2	0.98
Light (offices)	208	3	0.98

Crucial loads are set to high priority and must be supplied in all circumstances in order to avoid jeopardizing the production targets. These loads include the five induction motors with a total power demand of 250 kW located in the factory. The office equipment with a total power demand of 50 kW is set to a medium priority. These loads should be supplied during islanded mode, but they can also be disconnected if the available energy is insufficient to supply them. The remaining loads such as lights, air conditioning units and elevator are set to a low priority. These loads are disconnected from the grid during islanded mode. Both centralized and decentralized MG configurations will be subjected to the same case scenarios. Case 1: In this scenario, the MG is connected to the public grid and both factory and offices are operating at full load (400 kW). The loads are supplied by the generation units at peak power generation capacity (360 kW) and the public grid delivers the power needed to supply the remaining loads (40 kW). Case 2: In this scenario, there is no connection to the public grid. MG is operating in islanded mode and all the high and medium priority loads are connected to the MG grid. The five induction motors with a power demand of 250 kW and the office equipment with a power demand of 50 kW are supplied by the generation units at peak power generation capacity (360 kW).

5.1 Centralized MG

A centralized MG architecture for this industrial site is represented in Fig. 3A) and includes a centralized generation group with 360 kW of peak power capacity located at the generation bus, GEN1. This generation group acts as an uninterruptible power generator equipped with a bank of batteries and supplies the crucial loads in the main factory at bus LOAD5 and the office equipment at bus LOAD2 when the available energy is sufficient. The bus voltage profile obtained from the power flow study for scenario 1 and 2 are shown in Fig. 4 and Fig. 5, respectively.

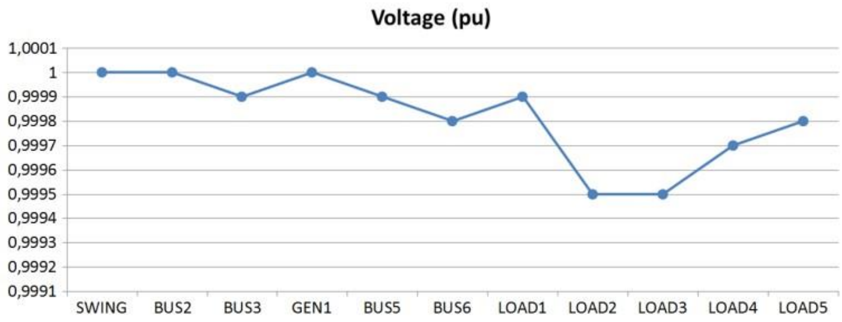

Fig. 4: Bus voltage profile in scenario 1 with centralized generation

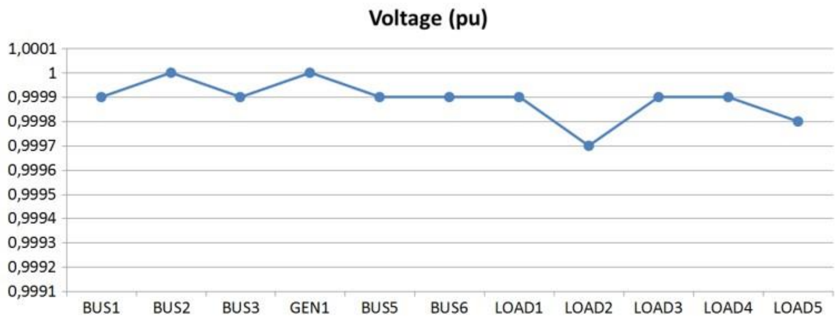

Fig. 5: Bus voltage profile in scenario 2 with centralized generation

As observed in Fig. 4, the bus voltage profile is almost ideal, approximately 1 pu. This is due to the small grid size. The lowest bus voltage value for scenario 1 is 0.9995 pu in bus LOAD2 and bus LOAD3. When observing the bus voltage profile for scenario 2 in Fig. 5, it is noticeable an improvement over the previous scenario, because the MG is operating in islanded mode and only the higher priority loads are in operation, meaning a decrease in the power demand. The lowest bus voltage value is now 0.9997 pu in bus LOAD2.

5.2 Decentralized MG

A decentralized MG architecture for this industrial site is represented in Fig. 3B) and includes four generation groups located at the generation buses, GEN1, GEN2, GEN3 and GEN4. The generation groups act as uninterruptible power generators equipped with a bank of batteries dispersed along the grid and close to the higher priority loads at bus LOAD5 and bus LOAD2. The bus voltage profile obtained from the power flow study for scenario 1 and 2 are shown in Fig. 6 and Fig. 7, respectively.

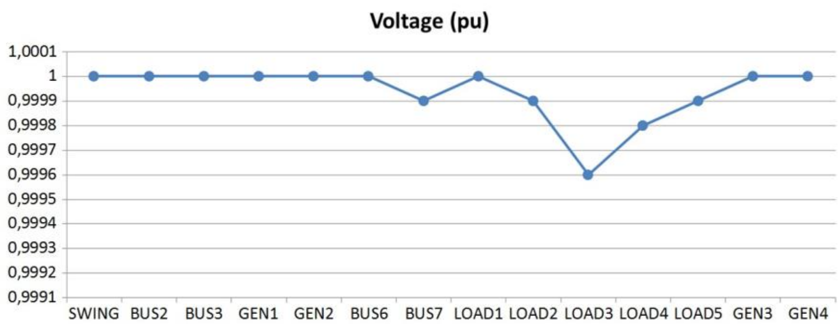

Fig. 6: Bus voltage profile in scenario 1 with decentralized generation

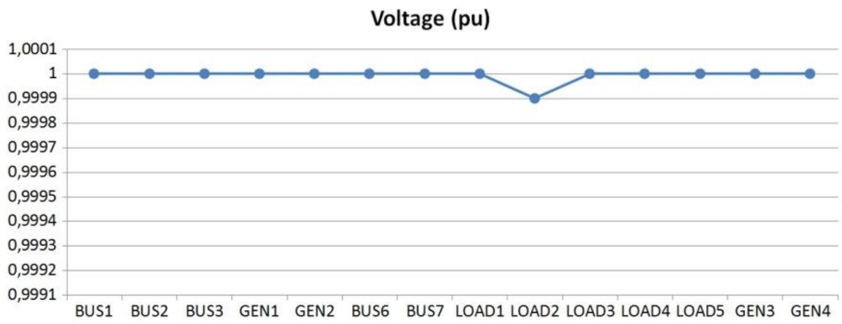

Fig. 7: Bus voltage profile in scenario 2 with decentralized generation

As observed in Fig. 6, scenario 1 with dispersed generation obtained a slightly better bus voltage profile than the same scenario with centralized generation. The lowest bus voltage value is 0.9996 pu in bus LOAD3. As expected, the bus voltage profile for scenario 2 in Fig. 7 shows an improvement over scenario 2 with centralized generation, because there are several dispersed generation groups supplying the higher priority loads. This scenario obtained bus voltages of exactly 1 pu with the exception of 0.9999 pu in bus LOAD2. In the scenario where the MG is operating in grid-connected mode, the public grid acts as a generator connected to a swing bus and it balances the active and reactive power by setting the voltage angle references for all MG buses. When the MG is disconnected from the public grid and there is no swing bus available, the MG bus connected to the generator with the largest capacity becomes the new swing bus and it is now responsible for regulating the active and reactive power.

When comparing the bus voltage profiles between the two MG configurations, the MG with dispersed generation groups obtained slightly better results than the MG with a centralized generation group. The decentralized MG provides better quality of supplied power to the loads with a slightly better bus voltage profile, since there are generation groups dispersed along the grid and located near the crucial and most demanding loads. Both MG architectures showed almost ideal bus voltage results due to the small grid size. However, the bus voltage profiles obtained from the power flow study showed relatively better results with the decentralized MG.

6 Conclusions

This paper presented an approach for the development of industrial MGs through a case study, where an industrial MG with centralized and decentralized deployment of energy sources is briefly analysed in different case scenarios. It was observed that a decentralized architecture can provide better bus voltage profiles than a centralized architecture. Also, in a decentralized architecture, the generation units can be placed near crucial loads to ensure their continuous power supply during emergency situations. Furthermore, the content of this paper addressed several aspects to assist in the study of industrial MG architectures. These aspects included a brief overview of the MG concept, as well as a characterization of control and communication architectures, and energy sources that can be adopted in MGs. Both the control and communication architectures may follow a centralized or a decentralized configuration. Moreover, the choice of an appropriate wired or wireless communication technology for a MG must be according to the installation costs and system specifications. The energy sources implemented in MGs are focused mainly on solar PV generation systems. PV technologies have been through a decrease in module prices and offer a long service life with low operation costs, but the availability of PV generation systems is dependent on the location and weather conditions. It is suggested the integration of hybrid generation systems into the grid to ensure the continuous power supply and overcome the dependency problem of PV systems. Taking into account the financial limitations of smaller enterprises, every increase in system cost needs to be carefully considered. A centralized deployment of the generation units is simpler and cheaper to implement. This approach might be the preferred solution for small scale grids. However, with a significant increase in grid size and number of loads, a decentralized deployment of several generation units along the grid may bring noticeable advantages in flexibility and quality of supplied energy.

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