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Review

Survey on microgrids: Unplanned islanding and related inverter control techniques

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A B S T R A C T

Nowadays, the importance of electrical generation based on renewable energies is increasing, due to its low emissions of greenhouse gases. At the same time, Distributed Generation and Microgrids (MG) are becoming an important research line because of their peculiar characteristics. MGs are composed of small power sources which can be renewable, placed near customer sites. Moreover, they have the inherent property of islanding: the disconnection of either the MG from the main grid or a portion of a MG from the rest of the MG. There are two kinds of islanding: intentional or planned (for maintenance purposes), and unintentional or unplanned. The latter is mainly due to disturbances and it is used to avoid damages in sources and loads. It is the most critical case because it must be detected as soon as possible to activate all the control systems which allow continuing the energy production and distribution despite the disconnection. In islanding, it is crucial to ensure the power and the electrical signal quality. In grid-connected mode, the inverters use the electrical signal of the main grid as reference. Once in islanding, the main grid reference is lost and new control techniques for the inverters are needed in order to obtain the correct values of voltage magnitude and frequency in the MG.

The main objective of this paper is to make a survey on MGs focussed on two important features: unplanned islanding and control of inverters in that scenario. The idea is to present the basic architectures and regulation techniques of MGs and to study the islanding behaviour, mainly the different detection techniques and the inverters' control once islanded.

1. Introduction

In the last years, the importance of Distributed Generation (DG) has increased considerably. The interest of DG grows when it is composed of different energy resources forming a Hybrid Energy System (HES), because they can easily support the electrical network in remote sites and rural areas. In this context, Microgrid (MG) concept makes reference to a group of loads and micro-sources which operate as a controllable system, providing electric power (and optionally heat, which is know as *cogeneration*) to its near area [1]. Nowadays it is proved that a system based on small-scale cogeneration can be more suitable than electrical only DG [2]. Combining cogeneration with absorption or engine-driven chillers allows setting up the concept of *tri-generation* and, in addition, the combination of different energy vectors, such as electricity, heat, cooling, hydrogen, etc., proposes a future energy scenario based on *multi-generation*.

Thus, a new paradigm of electrical network with distributed generation and the need to define its mode of operation appear. The utility considers the MG as a cell controlled by the power system. From the point of view of the customer, the MG can be implemented according to their needs, such as: to increase locally the reliability of the electric supply, to limit the feeder losses, to ensure the voltage quality or to provide uninterruptible power supply, among others. Moreover, from an economical point of view, MG has the advantage of deferring the network investments. It also contributes to adequate the generation because of its ability to control internal loads and generation [3,4].

One interesting property of MG is islanding: the disconnection of either the MG from the main grid or a portion of a MG from the rest of the MG. Islanding can be originated in a planned way or unintentionally and, in both cases, the isolated part can continue providing energy to its connected loads. This feature has clear advantages, but, at the same time, new difficulties which must be resolved.

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Finally, it is important to point that MGs are placed in the low voltage (LV)/medium voltage (MV) distribution networks. This has important consequences. Traditionally, the hierarchical structure used in electrical networks has carried out the most complex control systems with the greatest automation at high voltage (HV) levels. But now, with plenty of little energy sources connected at the distribution level, there are new challenges, such as system stability, power quality and network operation that must be resolved applying at LV/MV levels the control systems traditionally used at high voltage levels. In other words, distribution networks must pass from a passive role to an active one. This new active distribution network scenario is suitable to implement techniques of Demand Side Management (DSM) [5] in order to improve the efficiency of the MG.

This paper makes a survey on MGs, mainly focused on islanding concerns and inverter control techniques with the MG isolated. In Section 2, a description of the basic architecture of a MG, with the two different approaches, the European and the American one, is made as a start point of the study. Afterwards, Section 3 presents the basic applicable regulation techniques employed in MGs. Related with islanding, Section 4 explains different algorithms used to detect unplanned islanding. Once in islanding, one of the most important issues to be resolved is the control of MG's inverters. Therefore, in Section 5, a state of the art of different inverter control algorithms is made. Section 6 concludes this paper.

2. Basic architecture of a microgrid

The electrical micro-sources which exist in MGs are usually low power, under 100 kW, with interfaces based on power electronics in order to provide adequate control and flexibility. The typical sources used in MG are micro-turbines, photovoltaic (PV) panels, fuel cells and wind turbines. They have low greenhouse emissions, low power and high reliability. In addition, these sources can be placed easily near the customer's home. The basic architecture of a MG consists of a radial connexion of several feeders with their associated loads and micro-sources, as it was described by the first time in [1].

According with [6] an example with four feeders, A, B, C and D, is shown in Fig. 1. The voltage in a feeder is about 480 V, but it can be lower. Each feeder has a *circuit breaker* and a *power flow controller* commanded by the *energy manager*. If there is a disturbance into the MG, the *circuit breaker* is used to disconnect the correspondent feeder to avoid the propagation of the perturbation through the MG. In islanding, if there are variations in the connected loads, local micro-sources will either increase or reduce their production to keep constant the energy balance, as far as possible. That is not the case in grid-connected operation, because in this situation, the main grid compensates the increases or decreases of the load. The MG is connected to the distribution system by a *point of common coupling* (PCC). There is also a separation device known as *static switch*, which has the capability to island all the MG when faults or events described in the standard IEEE 1547 [7] occurs, or for maintenance purposes. If a feeder has sensitive loads (those that need uninterruptible power supply) connected, it will have local generators in order to avoid interruptions of electrical supply. To achieve an uninterruptible generation, those sources cannot be, for example, wind turbines or PV panels, because of the intermittence of the wind and the solar energy. Technically, there are batteries with enough energy saving capacity to act as a backup system when there is not enough wind or sunshine, but they are very expensive. One solution to avoid generation interruptions is the utilization of uninterruptible sources such as diesel generators, which are widely employed and known, or fuel cells, for example. From the basic architecture of MG described before, other approaches have been developed in Europe and USA in the frame of different projects. These new proposals are described in next Sections.

2.1. Architecture of MGs using microgrid central controller

The architecture of MGs that employs a *microgrid central controller* (MGCC) was firstly developed in the EU Microgrids Project [8] and proposes a hierarchical structure to guarantee a robust operation. An example of this architecture is shown in Fig. 2.

In these MGs, the most important element is the MGCC (the first hierarchical level), which is installed on the side of the medium voltage/low voltage (MV/LV) substation connected to low voltage line (LV). Its function is to carry out a high level management of the MG operation by means of technical and economical functions. In a second hierarchical level are *micro-source controllers* (MC) that control, obviously, the micro-sources and the energy storage systems. Finally, each load or set of loads is controlled by a *load controller* (LC). To perform the interchange of information between

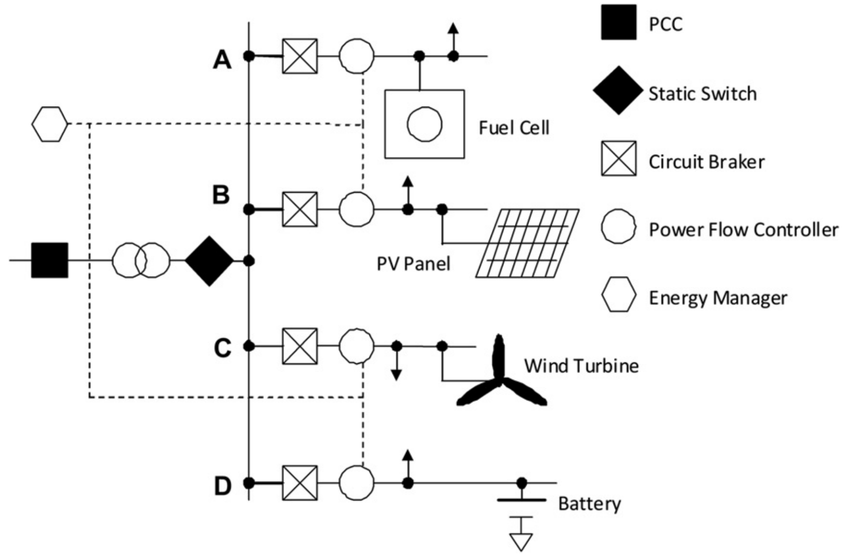

Fig. 1. Basic architecture of a MG.

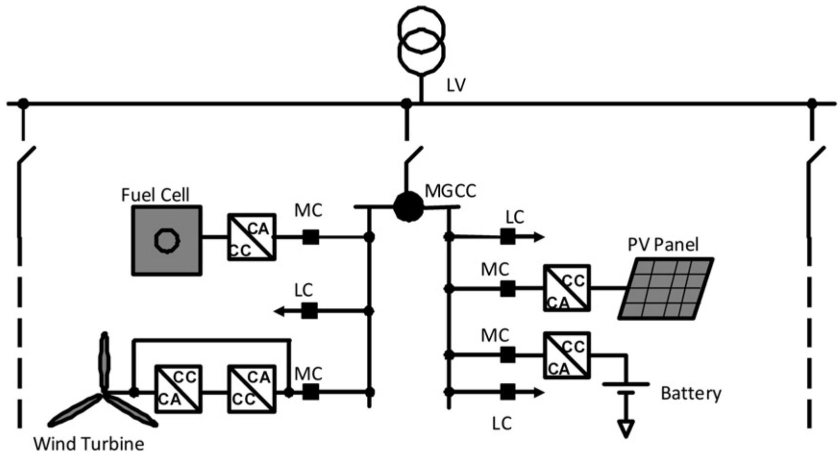

Fig. 2. Architecture of a MG with MGCC.

the MGCC and the rest of controllers, a communication network is needed. That interchange occurs as follows.

- The MGCC establishes the most adequate technical and economical policies to achieve, and fixes the correct set points for MCs and LCs.
- The set points are sent to the MCs and LCs.
- From the set points, each LC tries to obtain the best service while the MCs regulate the production levels of real and reactive power of the micro-sources.

It is important to say that the amount of data interchanged by all the controllers is small, because the usual information consists of messages with set points for MCs and LCs, as well as requests sent by the MGCC to the MC an LC to know the current and real/reactive power levels.

2.2. Architecture of CERTS microgrid

CERTS microgrid (CM) concept proposes the unlimited installation of distributed energy equipments in the electrical grid [9], based on the architecture depicted in Fig. 3. CM paradigm permits a smoothly islanding, provides electricity to relatively small installations (under 2 MW of peak), and without complex and expensive control systems. The most important characteristics of CM are as follows.

- The operation of the generators is controlled locally by power electronics devices that include droop regulation.
- Plug-and-play functionality, allowing that any device, independently of its technology or manufacturer, could be connected to the CM.

The CM has not a continuous communication between controllers as in the architecture with a MGCC. Each source has an individual micro-source controller system (*power and voltage controller* in Fig. 3) which receives the set point provided by the *energy manager* only just before the start of source operation. This configuration increases the system's reliability in comparison with centralized approaches: if the *energy manager* suffers a shutdown, the CM continues operative because the *power and voltage controllers* employ the last set point given by the *energy manager* before its failure. Other difference with the *EU microgrid project* proposal is the plug-and-play option, which supposes more simplicity to connect sources and loads to the MG, but more complexity in each device because a level of intelligence is needed.

3. Microgrid's regulation systems

There are two kinds of micro-sources in MGs.

- *DC sources* (fuel cells, photovoltaic panels and batteries).
- *AC sources* (variable speed micro-turbines like wind turbines) which produces variable-frequency electrical signal which must be rectified.

In both cases, the DC signal obtained directly or after rectification is converted again into an adequate AC signal by means of a *voltage source inverter* (VSI). The general model of a micro-source is shown in Fig. 4.

It consists of three basic components: prime mover, DC interface and VSI which is connected to the grid through an inductance. The VSI is able to control the phase and magnitude of its output voltage V and from system voltage E, and from the inductance's reactance X, it can determine the real power P and reactive power Q flows from the micro-source to the grid. P and Q values are linked, as it can be deduced from the Eqs. (1)–(3).

$$P = \frac{3}{2}\frac{VE}{X}\sin\delta_p \tag{1}$$

$$Q = \frac{3}{2}\frac{V}{X}(V - E\cos\delta_p) \tag{2}$$

$$\delta_p = \delta_V - \delta_E \tag{3}$$

In Eq. (3), δ_V and δ_E are the angles of V and E, respectively. For small variations, P mainly depends on power angle δ_p whereas Q depends on voltage converter magnitude, V. These relationships allow us to establish feedback loops in order to control output power and MG voltage in islanding.

3.1. Voltage versus reactive power droop control

Reactive currents are problematic for the power system, especially when they circulate between the sources. This problem is avoided in the main grid because of the high impedance value between generators, which is not the case in MGs. One possible solution to limit reactive currents when the impedance value is not high enough is the employ of local voltage regulation, for example, a voltage versus reactive power droop control.

The basic controller characteristic is in Fig. 5, according to Eq. (4). V_0 and Q_0 are the grid voltage and reactive power set points, respectively.

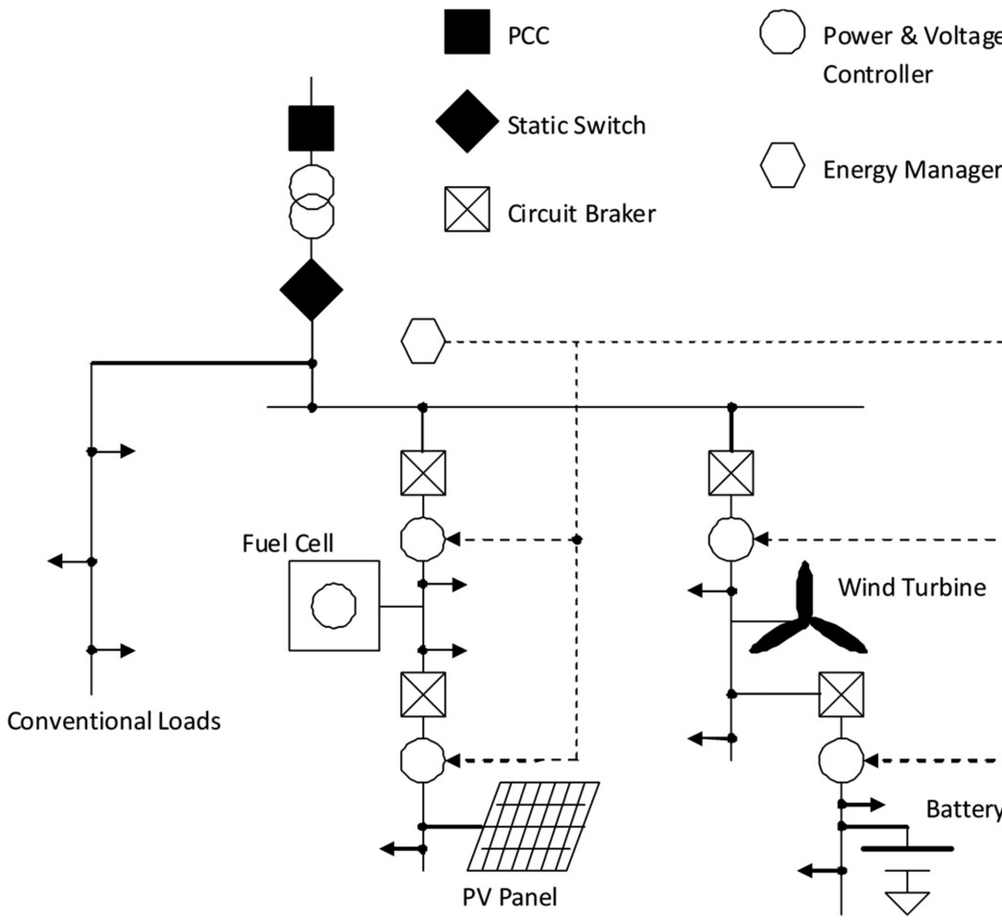

Fig 3. Architecture of CERTS MG.

If the reactive power generated by the micro-sources increases, the local voltage must decrease, and conversely, if the reactive power decreases, the voltage must increase.

$$V - V_0 = -k_q(Q - Q_0) \tag{4}$$

3.2. Frequency versus real power droop control

It is also necessary to implement a frequency versus real power droop control. In Fig. 6, and according to Eq. (5), it is depicted the characteristic (P, ω) for a micro-source.

$$\omega - \omega_0 = -k_p(P - P_0) \tag{5}$$

ω_0 and P_0 are the rated frequency and real power set points, respectively.

The slope is chosen in order to obtain a little frequency variation $\Delta\omega$ when the power varies between zero and its maximum value P_{max}.

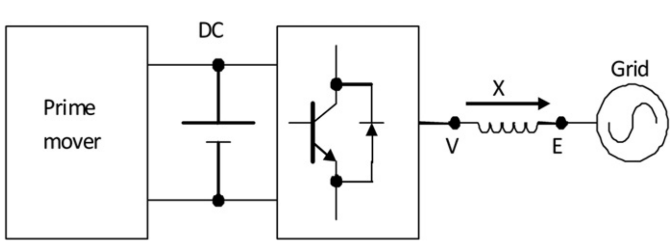

Fig. 4. General model of a micro-source.

As it has been said before, a MG can operate in grid-connected mode or in islanding. With the cut of power due to a disturbance such as voltage shutdowns, blackouts, etc., the MG will be automatically islanded.

There are two possible scenarios for a MG before islanding: the MG is exporting energy to the grid, or the MG is importing energy from the grid. Depending on the case mentioned before, the MG has different behaviours once in islanding.

- MG exporting energy: in islanding, the generated power will decrease (the local loads need less power). The local source

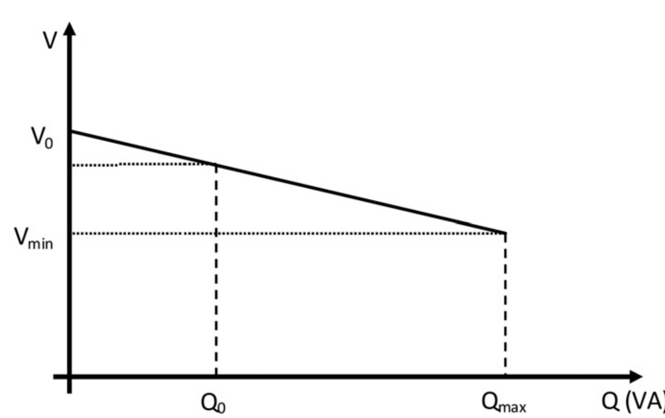

Fig. 5. Voltage versus reactive power droop control characteristic.

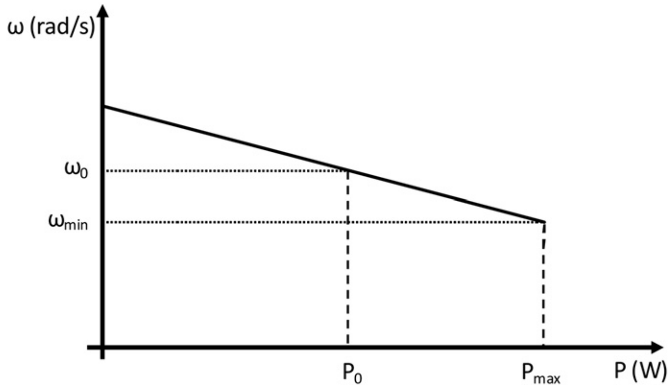

Fig. 6. Frequency versus real power droop control characteristic.

controller detects the power diminution and increases the generated frequency.
- MG importing energy: in islanding, the generated power will increase, so the frequency will be decreased.

After a transitory period, the MG will reach a stable frequency.

3.3. Applicability of droop regulation techniques in MGs

Once described the basic droop regulation techniques, it is crucial to point up that voltage and frequency control is problematic in islanding. The conventional droop methods described in Sections 3.1 and 3.2 are useful in grid-connected mode, but are they applicable in islanding [10]? In fact, Eqs. (4) and (5) have been obtained for electrical grids with inductive impedance ($X \gg R$), which is the case of HV lines. However, MGs are placed in LV or MV lines. The impedance of MV lines has a resistance and reactance nearly equal ($R \approx X$), and LV lines are predominantly resistive ($R \gg X$). Therefore, droop regulation techniques change in resistive lines: reactive power Q depends manly on δ_p and real power P depends on converter's voltage V [11]. This fact suggests to use, in MGs, voltage vs. real power and frequency vs. reactive power droops, called *opposite droops*, instead of *conventional* ones (ω vs. P, V vs. Q). Fortunately, conventional droops are operable in LV grids and MGs: it is possible to vary the voltage of generators exchanging the reactive power. Each generator has a tuned reactive power to obtain a voltage profile which matches the wanted real power. In LV grids, Q is a function of δ_p, which is adjusted with the ω vs. P droop. So, it is necessary an indirect operation of the droops with an only condition: frequency and voltage droop factors must have the same sign [12].

4. Islanding detection algorithms

As it has been commented before, islanding of a MG composed of distributed generation systems takes place when a portion or the whole MG is disconnected from the main grid. The distributed generators continue providing energy into the isolated section. Islanding can be either planned or unplanned [13]. In the case of planned islanding, it is possible to make a correct load share between DG units and the grid. Thus, islanding operation occurs without transients and the MG continues operating as an autonomous system. Planned islanding and the later operation of the MG are exhaustively studied in [14]. It is possible to make a planned islanding for maintenance purposes, among others.

Unplanned islanding is due to disturbances in the grid, such as blackouts, voltage shutdowns, short-circuits (between two phases or between one phase and the neutral in three-phase systems), etc. Before islanding, the operation conditions of the MG can be varied, depending on the distribution of electrical loads between DG units or if the MG is importing or exporting energy from/to the grid. Definitively, there is not a predefined scenario before islanding. In addition, the disconnection operations cause a large amount of transients. The severity of the transients suffered by the MG after an unplanned islanding depends on: operation conditions before islanding, kind and localization of the disturbance that starts the islanding, interval until islanding detection, commutation operations subsequent to a disturbance, kind of DG connected to the MG. Once in islanding, the reconnection to the main grid is only possible when this has been restored. In order to consider valid the restoration, both frequency and voltage must recover their nominal operation values after an interval of time, usually fixed in 5 min [7]. The reconnection must be made when the MG and the main grid are synchronized in the PCC in terms of frequency and phase of their respective voltages. Table 1 [15] shows the necessary limit values of frequency, voltage and phase to achieve a synchronous interconnection between MG and the main grid.

There are several islanding detection techniques, useful to know when the unplanned islanding has occurred, which can be classified into three groups: passive methods, active methods, and utility level methods [16,17]. None of the later techniques is the best by itself in terms of performance, reliability, cost (amount of equipment or infrastructure needed to make it work) and DG technology neutrality (possibility of employing the detection algorithm in all kind of DG interconnection schemas). However, all of them must accomplish the standards IEEE 1547 [15], IEEE 929-2000 [18] and UL 1741 [19].

Passive islanding detection algorithms, which operate measuring local values of voltage, frequency or phase, are the cheapest and technologically neutral, but their effectiveness is not the best. On the other hand, active algorithms, which employ varied techniques such as injection of active signals, among others, are considered more effective to detect islanding than passive techniques. However, they are more expensive and no technologically neutral. In the next sections, several islanding detection algorithms and the none detection zone (NDZ) are described.

4.1. Evaluation of passive algorithms. Definition of the none detection zone (NDZ)

In this section, the effectiveness of three passive methods and the NDZ concept [20] are presented. To evaluate the accuracy of the islanding detection algorithms, it is necessary to follow this procedure.

- Defining the evaluation index. This index refers to the NDZ, that is to say, given a variation of real power ΔP and a variation of reactive power ΔQ, the frequency and voltage deviations in islanding must be large enough to detect this islanding within an adequate interval of time.
- To refer the NDZ of each algorithm in terms of power unbalance to evaluate its performance. Therefore, the smaller is the NDZ, the better is the algorithm.

Table 1
Limit values for synchronous interconnection between MG and main grid.

Aggregate rating of DR units (kVA)	Frequency difference (Δf, Hz)	Voltage difference (ΔV, %)	Phase angle difference ($\Delta \Phi$, °)
0–500	0.3	10	20
>500–1500	0.2	5	15
>1500–10000	0.1	3	10

The NDZ represents the interval in which is not possible to detect the islanding once it has occurred. The objective is to reduce the NDZ to improve the detection algorithm. It is important to point that the NDZ is almost equal to zero for active algorithms and utility level methods, therefore, their effectiveness is higher.

The three passive techniques that are going to be studied are *under/over voltage detection*, *under/over frequency detection* and *phase jump detection*.

4.1.1. "Under/over voltage" and "under/over frequency" algorithms

In real systems, a power difference between DG output and the load of the electrical system exists, but is not problematic because it is balanced by the grid. Once in islanding, voltage and frequency suffer variations and take new values (V', f').

When the power unbalance is high enough, the values of V' and f' go out of their nominal ranges, and the islanding of the MG can be detected. Eqs. (6) and (7) show the relationships between the power unbalance thresholds and the voltage/frequency thresholds:

$$(V/V_{\max})^2 - 1 \le \frac{\Delta P}{P} \le (V/V_{\min})^2 - 1 \tag{6}$$

$$Q_f\left[1 - (f/f_{\min})^2\right] \le \frac{\Delta Q}{P} \le Q_f\left[1 - (f/f_{\max})^2\right] \tag{7}$$

where $V_{\max}$, $V_{\min}$, $f_{\max}$, $f_{\min}$ are the maximum and minimum thresholds of voltage and frequency, respectively. Here, P depends on V and Q depends on f, which is the case for low voltage electrical networks (MG).

The power unbalances presented in Eqs. (8) and (9) are obtained considering the limit values for a grid of 50 Hz given in a particular scenario [21] ($V_{\max} = 120\%$V, $V_{\min} = 80\%$V, $f_{\max} = 51$ Hz, $f_{\min} = 48$ Hz). The quality factor Q_f is considered 2.5.

$$-30.56\% \le \frac{\Delta P}{P} \le 56.25\% \tag{8}$$

$$-2.13\% \le \frac{\Delta Q}{P} \le 9.71\% \tag{9}$$

If real and reactive powers variations are into the specified limits, then the resulting voltage and frequency will remain into their accepted range once the MG is in islanding: the islanding has occurred without detection. In other words, Eqs. (8) and (9) represent the NDZ for these algorithms.

4.1.2. "Phase jump" (PJ) algorithm

Phase jump islanding detection passive algorithm detects the discontinuities in the phase of the electrical signal when the MG is disconnected from the grid. This PJ algorithm is based on the Eq. (10).

$$\left|\arctan\left(\frac{\Delta Q/P}{1 + \Delta P/P}\right)\right| \le \theta_{\text{threshold}} \tag{10}$$

$\theta_{\text{threshold}}$ must be chosen correctly in order to minimize the NDZ of the algorithm without reduction of the effectiveness in the islanding detection.

4.2. Active islanding detection algorithms

Active islanding detection algorithms are based on intentioned modifications of one or several parameters of the electrical signal in the MG, mainly the frequency and the magnitude of the current or voltage. When the MG is connected to the grid, these modifications have no effect on the electrical signal. Nevertheless, in islanding, the perturbations caused in the electrical signal of the MG are strong enough to detect the islanding. The description of two typical active algorithms is as follows.

4.2.1. Algorithm based on current injection

One of the techniques used in active algorithms consists of injecting a signal in the system. A usual method employed is the injection of a perturbation current [22]. This kind of algorithms is applicable at distribution grid level, where voltage source inverters are used as interfaces with the main grid. The operation is based on an injection of a perturbation in the system through the current controllers of the converters. The reference system employed is the $d-q$ frame, and the impact of the perturbation is monitored at the PCC of the evaluation circuit shown in Fig. 7.

The algorithm operates as follows: in the circuit depicted in Fig. 7, the RLC load obtains a power factor equal to 1 for a 50 Hz fundamental component of the current supplied by the VSC. Considering the MG connected to the grid, if a sinusoidal perturbation with a frequency not equal to 50 Hz is injected through the current controllers of the VSC, this current $i_{\text{disturbance}}$ is absorbed by the grid.

Nevertheless, in islanding there is no connection with the grid and the perturbation current flows through the load RLC (Fig. 8),

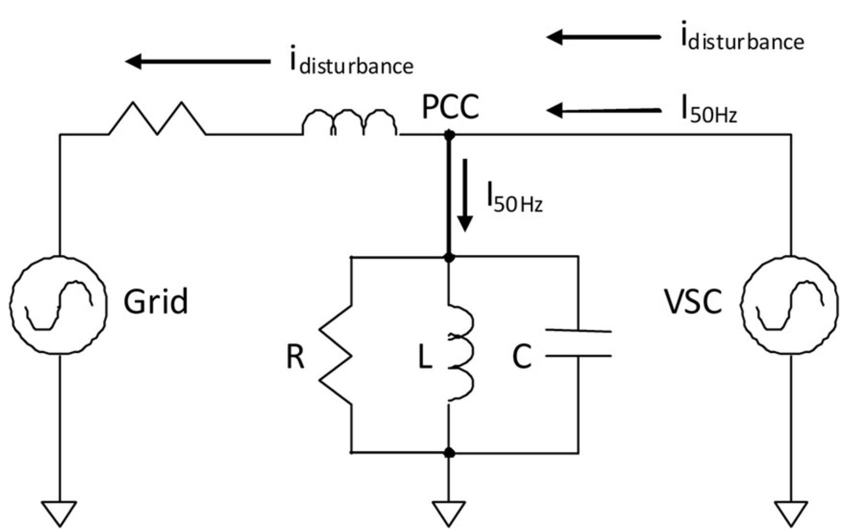

Fig. 7. Signal perturbation path in grid-connected mode.

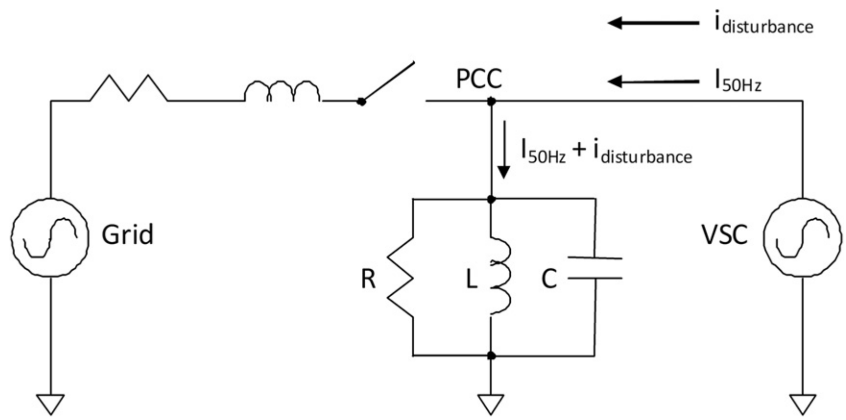

Fig. 8. Signal perturbation path in islanding.

making possible the islanding detection. The perturbation is stopped just in the moment of islanding detection to avoid disturbances in the MG.

4.2.2. *Sandia National Laboratories algorithm*

Another interesting islanding detection active algorithm has been developed by the Sandia National Laboratories of the USA. Originally, this algorithm was created in order to avoid the accidental islanding of power systems based on photovoltaic panels. In [23] there are some propositions about how to avoid islanding in photovoltaic installations: the idea is to monitor the voltage and frequency values at the inverter output in order to prevent the inverter operation when those values reach unacceptable magnitudes. This algorithm is adequate to be employed in single-phase inverters (used in photovoltaic generation systems) for islanding detection purposes. The algorithm consists of two schemas, *Sandia frequency shift* (SFS) and *Sandia voltage shift* (SVS), and the islanding detection is based on a voltage and frequency drift accelerated by means of positive feedbacks. When the system is grid-connected, the feedback has no effect in voltage and frequency magnitudes because they are fixed by the utility. However, in islanding, the feedback makes those values unacceptable and, subsequently, the disconnection can be detected. This method can be also used in three-phase systems: [24] shows a solution for three-phase DG by means of a three-phase PLL in a synchronous reference frame. The operation of the Sandia algorithm is exhaustively described in [25].

4.3. *Utility level methods*

Utility level methods employ techniques based on communication signals or different alarms to detect the islanding.

4.3.1. *Islanding detection by means of communication signals*

Communication signals are useful to detect the islanding of a MG: a transmitter sends a continuous low voltage signal (which can be also used for management purposes, such as Demand Side Management) through the electrical lines. When the MG central controller receiver does not receive that signal, it can be considered that the MG is islanded, and the inverters will receive the set points to operate in islanding. The signal must have several properties to be useful for the islanding detection and in order to be propagated through all the distribution lines.

- It must be sent continuously to avoid false islanding detection.
- The frequency of the signal must be low, because of the inductances of the transformers, which act as low-pass filters.

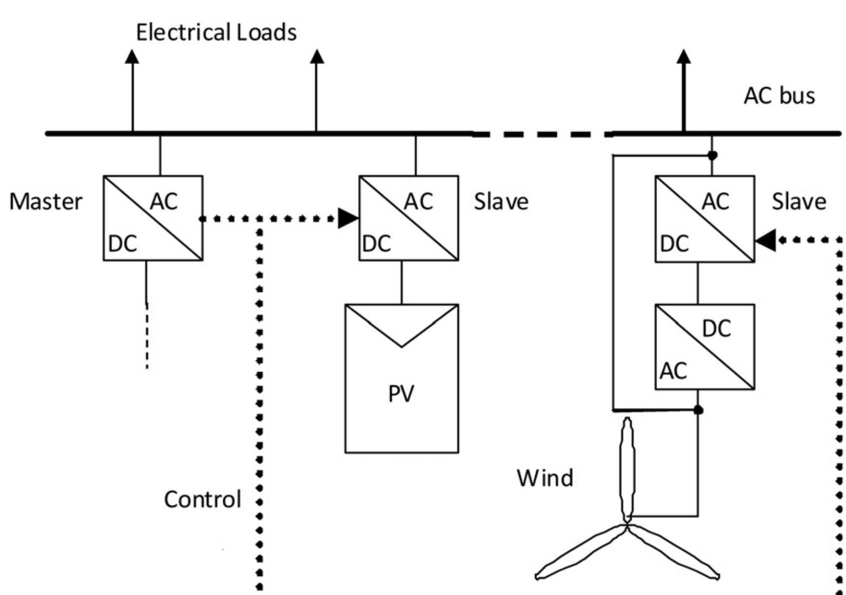

Fig. 9. Single master operation.

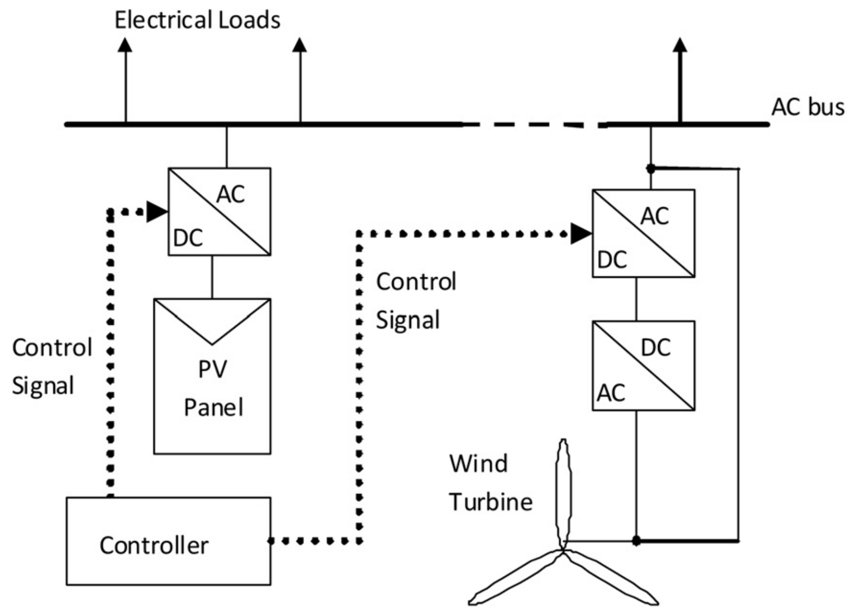

Fig. 10. Multi-master operation.

- The signal must travel from the grid to the load.

4.3.2. SCADA: supervisory control and data acquisition

Employing SCADA techniques to detect the islanding is very simple: if the voltage sensitive devices placed in the inverters detect a loss of voltage, audible alarms are started in order to notify the islanding. Moreover, SCADA systems can assure the synchronism between the MG and the electrical grid in order to avoid differences of phase, making easy the reconnection once the disturbance has disappeared.

5. Control techniques for inverters in a MG

When the MG is in islanding, it is necessary to apply a particular control. The objectives are to obtain a frequency deviation equal to zero and to maintain the voltage value between some specified values. To assure this, the inverters must find new voltage and frequency references, maintaining a good power quality.

5.1. Voltage source inverters and MGs

A MG in islanding can be considered as an inverter dominated system, because their electrical signals are controlled by the same power electronics which acts as interface between the MG and the grid in grid-connected mode. During the grid-connected operation, all the inverters in the MG operate in PQ configuration, and use the grid electrical signal as reference for voltage and frequency. However, in islanding, the inverters lose that reference. The system which can operate either grid-connected or in islanding is the *voltage source inverter* (VSI), due to their special operation characteristics: it can work connected to the grid without injections of real or reactive power, and once in islanding, the difference between produced and consumed power in the MG can be used to calculate its output signal.

There are two general inverter coordination strategies to manage the simultaneously operation of them [26].

1. *Single master operation*: a master VSI fixes voltage and frequency for the other inverters in the MG. The micro-sources are connected to the rest of inverters, which operate in *PQ* configuration according to the references given by the master. Fig. 9 shows this schema.
2. *Multi-master operation*: in this case, several VSIs operate as master and are controlled by means of a MGCC which chooses and transmits the set points to all the VSIs in the MG (Fig. 10).

Several techniques have been developed and proposed by the scientific community during last years in order to control the inverters in islanding and to obtain voltage and frequency references. In next section, there is a description of the most relevant techniques.

5.2. Control techniques for VSI in islanding

The main function of a VSI in a MG is to obtain a signal with the correct voltage and frequency values in order to supply the

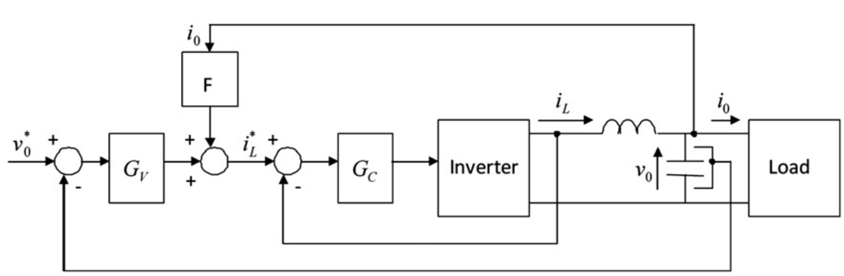

Fig. 11. Multi-loop control for a stand-alone inverter.

electrical loads. Fig. 11 depicts a block diagram of an inverter including the low-pass filter LC.

The most employed method to assure the system stability and to improve the dynamic performance is to use two feedback loops. The outer loop regulates the output capacitor voltage v_0. After the addition with the measured output current it sets the reference inductor current i_L^* for the inner control loop. The magnitude and frequency of the filter output voltage reference v_0^* are kept constant, but their values could vary if an additional droop control (described in Section 3) is used. Blocks G_V and G_C are the voltage and the current regulators, respectively.

There are several possibilities to implement the voltage and current regulators. One of the most typical solutions is to employ Proportional Integral (PI) controllers. In [27], a real-time space-vector-based control technique, useful for unbalanced and non-linear loads is presented, using a PI controller to obtain a faster response and a higher stability. The approach described in [28] proposes a control system for single-phase VSIs. Again, a multiple feedback loop is used with PI controllers. However, it is important at this point to say that PI controllers have a permanent steady state error impossible to eliminate for AC signals. In addition, this problem is increased when the loads generate harmonics, because each one has a frequency different from the fundamental.

Control techniques based on multiple rotating frames reduce some of the limitations of the PI techniques described before. However, the complexity of the system is increased.

In this context, Green et al. [29] present a control method based on nested feedback loops, with a transformation from $a-b-c$ reference frame to $d-q$. The inverter current is controlled by the inner loop while the outer loop manages the voltage, as in the classic VSI control techniques. An interesting characteristic of this method is the possibility of parallel operation with multiple inverters adding additional communication loops.

A very similar solution is proposed in [30]: in this case, the frequency is controlled by means of an internal PLL oscillator and the voltage in the islanded MG is regulated using a feedback loop.

Standard linear control has been also employed to develop VSI controllers, as in [31]. The H_∞ *design procedure* has been applied in [32] in order to control a single-phase inverter. It also considers the possibility of having disturbances in the electrical loads. *Discrete-time sliding mode control* [33] is a robust algorithm which has been used to control inverters [34]. Finally, Dai et al. [35] have developed a complex control technique for three phase four-wire inverters which combines two control loops. The inner loop is a current loop based on *discrete-time sliding mode controller* (DSMC) and the outer regulates the voltage using a *robust servomechanism controller* (RSC). The aim of this approach is mainly focused in the reduction of the Total Harmonic Distortion (THD).

6. Conclusions

This article has carried out a survey on one of the most promising electrical systems for the next years, the MGs. The MG paradigm supposes an enormous revision of traditional electric network concepts, and new solutions must be proposed and found. In this way, there are two approaches based on the same architecture but with some differences about management and control: the European solution using a MGCC, and the CERTS Microgrid proposed in USA. Both of them need a control of real and reactive power. To achieve that, two proposals have been presented: *frequency versus real power droop control* and *voltage versus reactive power droop control*, techniques traditionally employed in HV electrical lines. However, MGs are MV/LV lines, so those control techniques must be applied carefully.

Islanding is a powerful feature of MGs which originates at the same time the principal problems to resolve. The first step is to detect the unplanned disconnection from the grid to start all the needed mechanisms which ensure a successful islanding. The electrical generation in islanding is not interrupted, so the process must be transparent for the sources and loads connected to the islanded part. Islanding detection algorithms are used in order to detect the unplanned islanding, existing three main categories: passive, active and utility level methods. In addition, the NDZ of the algorithms has an important influence on the accuracy of islanding detection. Passive algorithms have a large NDZ, thus, their effectiveness is not the best. On the other hand, active algorithms and utility level methods have a negligible NDZ. In general, it is necessary to find a balance between effectiveness and simplicity, depending on the needs of each MG.

Inverters play an important role because they act as interface and fix the voltage and frequency of the signal into the MG. In islanding, the reference given by the grid is lost and control techniques are requested by inverters to create new references which will guarantee the good quality of the electrical signal in the islanded part. The scientific community has proposed many techniques based on traditional or more complex methods. To conclude, it is important to point the amount of new perspectives opened by MGs in the electrical grids domain, as well as for the customers. Nevertheless, more research is still needed until having MGs systems widely spread all over the world.

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