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Contents

1. Initial assessment of µGrids

The main reason that traditionally has justified the increasing development of energy supply systems based on alternating electric fields (AC) is the simplicity and reliability for voltage level change while maintaining the apparent power value. This 'voltage control' favours the long distance transmission of the bulk energy, maintaining at the same time, the joule losses at low levels.

However, it is important to take into account that the overall cost of any energy transmission system is not only related to the losses, but also to other issues such as the lack of quality of supply, the cost of the equipment required to operate the system, the ancillary services supporting its correct operation…

It is known that in order to keep the reliability and quality on the electrical energy supply, the transmission networks are usually meshed through the interconnection of all existing generation resources. A meshed network on the high voltage level ensures that a shutdown of a part of the available energy (wind, tripping of a reactor, turbine...) is shared in the system, diminishing as a result, its disturbing effects.

Nevertheless, the development of Distributed Energy Resources (DER) seems to modify the traditional structure of the electrical systems because in these cases, the resources are coupled close to the consumption centres or around the end users (namely, low power rating systems based on solar or wind energy). This dispersed generation is generally interconnected to the line through power electronic devices that could be enhanced to perform other functions apart from the energy injection.

Combined Heat and Power (CHP) devices allow heat and power generation and optimal recovery of waste heat. Although small scale thermal generation of electricity is unlikely to be competitive with central station generation, the possibility of recovering the waste heat, especially in absorption cooling systems, might focus the economic scales towards DER.

It necessary to centralise and synchronise those emerging resources in order not to deteriorate the network reliability and stability (line overloading, voltage beyond limits …). This problem could be efficiently solved if this energy is managed as a whole, that is, as a Virtual Power Plant. This way, the market participation of this kind of resources is also facilitated, allowing them the sale of the generated energy and the offer of ancillary services such as voltage or frequency control.

One possible solution of the arising problem is the integration of the energy resources in autonomous µGrids instead of in the traditional, unique and univocal network.

µGrids are low voltage networks where the electrical energy is generated close to the consumption centres at the time that enhances the quality of supply endowing the µGrid with capabilities to operate autonomously (for instance when a voltage perturbation appears in the main network), Figure 1.

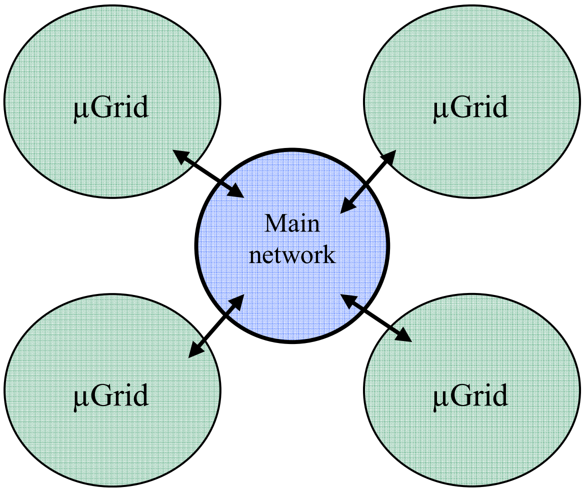


Figure 1: µGrid based electrical system

In a µGrid that operates as a whole, the power generation and consumption can be matched more accurately (since storage capabilities, heat generation of µCHP… can be available as reserve generation). This way, a more efficient system operation and a higher penetration of renewable energy resources is possible.

In this situation, an optimum energy usage can be obtained because the network is able to manage its own energy consumption and generation, facilitating as a result, the synchronization of not mandatory consumptions according to the power availability. Once generation and consumption are merged in the same decision process, the use of the energy is further optimized since the demanded energy can be regulated as an indirect generator. This way, the maximum revenues can be obtained.

In a μGrid, the energy balance is maintained through active plug and play electronic interfaces that allow operation without requiring the employment of a tight central active control or a fast communication. These interfaces allow the connection and the disconnection of the devices without needing any reconfiguration of the existing or the new equipment.

Literature has already focused the attention on some of the main problems that nowadays influence the low voltage AC networks in order to justify the development of the Direct Current (DC) networks as a solution to deal with them [3]. These problems are mainly the lack of quality of supply, the losses produced along the line due to the pollution caused by harmonics, unbalanced and reactive powers and line overloads due to that pollution. Literature also reviews the existing systems that can help to mitigate these difficulties such as passive or active filters, Uninterruptible Power Supply systems (UPS), "Network friendly" rectifiers…. Finally, DC networks are analysed as a real alternative to solve the deviation from the ideal operation of the previously mentioned networks.

However, when several resources are connected to a grid whose voltage and power are not balanced by a main converter (or a group of main converters), every resource connected to the network take part on the voltage and power control. The droop characteristic -commonly used within the supplying of active and reactive power as a function of frequency and voltage respectively- could be applied under the DC voltage [4]. Nevertheless, when the short-circuit power at the connection point differs from one resource to other, the power distribution might not be perfectly symmetrical, requiring consequently, the employment of special controls and algorithms to correct the deviation [5].

The purpose of this work is to study the achievements of the μGrids based on DC voltage (basically at the level below some kV). The μGRID issues such as voltage control, quality of supply, economics and control simplicity (plug & play devices, lack of reactive power components…) are analysed.

2. Advantages of DC based µGrids

In this chapter, the advantages related to the energy distribution and consumption based on DC fields are analysed in detail.

One of the main barriers for distributed generation integration in AC networks is the constraints caused by the alternate voltage supporting the system. This characteristic makes the system complex because any device connected to it must be capable of synchronizing itself to the network voltage (in magnitude, phase and frequency). For this purpose, a digital controller is required in order to determine the rotating vector that characterises the network voltage at any time (not only the position of the voltage vector, but also the rotating direction), so that the connection of the equipment to the main system is carried out without jeopardizing the operation of the network and the equipment connected to it. The cost associated to the synchronization requirements might be reduced or even eliminated in DC networks.

In addition to this, the filtering process and the storage capabilities are less efficient and more expensive when they are based on AC voltage. The line becomes polluted because of different currents that appear and which are not directly required as active power demand. Those are basically composed by the emission of harmonics of non-linear loads (for instance AC to DC converters), and by the reactive energy associated to the loads when they operate in alternate fields.

Another 'potential' disadvantage of AC based µGrids in contrast to DC systems is their slightly lower system efficiency when loads are based on DC fields. This is due to the required transformation of the electricity between both fields. This effect is more important in systems where a large percentage of the consumption occurs at a different time of the production (such as in PV systems with high consumption at night) being the remaining energy stored in batteries [20]. This issue will be analysed in more detail in section 2.1.2.

2.1.1. Pollution decrement through the decoupling between the main system and the µGrid

The mismatch between the AC supply and the increasing number of non-linear electronic loads results in electro-magnetic compatibility (EMC) and power quality problems such as low-frequency harmonics which make neutral conductors become overloaded and protections malfunction. Most of the loads which are connected to the low voltage AC system, must convert internally this voltage into a DC one in order to operate properly. This process has the disadvantage of generating harmonics which are different from the fundamental AC component. Those harmonics, which are not required for the optimal operation of the system, make the leading current on the line grow and thus the losses associated to the energy transmission (lines, transformers, neutral overloading...) also increase.

At the same time, most of the loads connected to the line (and the line itself), consume reactive power which causes overloads on the lines as well as an increment on the joule losses and a worsen on the voltage control. [3].

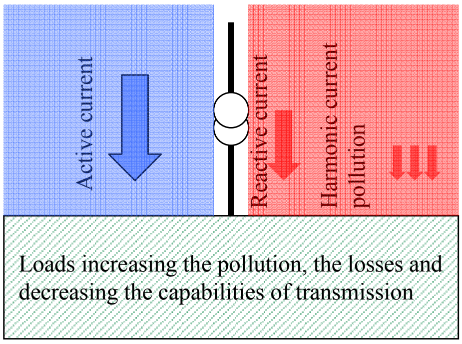


Figure 2 Line pollution due to non-linear loads

This reactive current, the same as the current harmonics components, can be locally generated at the consumer's centres instead of overloading the entire system (cables, transformers, generators) through the placement of dedicated devices based on power electronics close to the loads.

There are several ways to decrease the pollution leading the lines and to ensure that the load presents a pure resistive characteristic (that is, there are not reactive power consumption neither harmonics) [3].

The first option is the employment of active filters (Figure 3). Usually, several of these systems are required, increasing as a consequence, the overall cost of the electrical system.

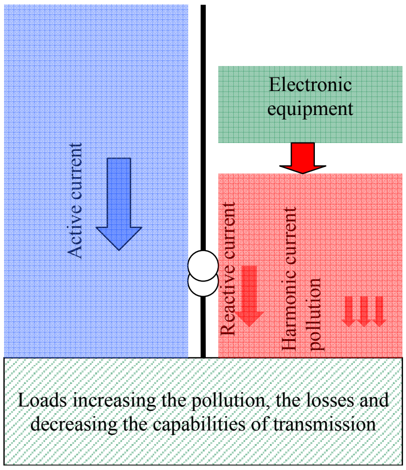


Figure 3: Electronic equipment for diminishing the pollution

Another option that could help to avoid the generation of this current pollution is the extended use of controlled µGrids based on DC voltages. These networks are characterized by the compulsory decoupling of the µGrid from the main network through an AC/DC converter, fact that is not ensured on AC voltage based µGrids.

A DC system, although it does not completely eliminate required the power conversion to feed the loads, it removes the AC-DC conversion stage in most of the loads. A central converter is still needed to interface with the utility AC grid. However, the interface can be designed so as to achieve high power quality on both, the AC side (low harmonic content) and the DC side, i.e. keeping constant the DC voltage that feeds the loads in spite of the faults and the disturbances of the AC side.

The converter in charge of isolating both networks is based on power electronics and can not only decouple both networks but also control freely the reactive power injection/absorption (helping the network operator with ancillary services). This way, the emitted harmonics are reduced and the system is operated on the range of few milliseconds.

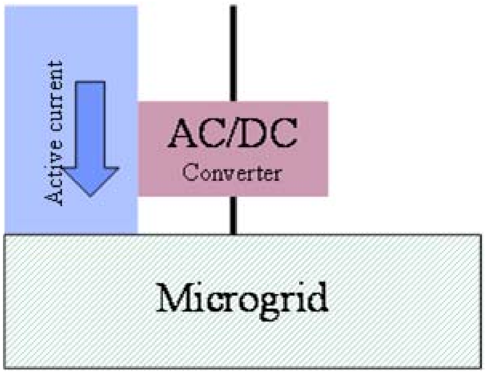


Figure 4: Isolation of the current pollution into the µgrid background

This allows confining the current pollution inside the µGrid, 'sailing' the electrical energy along the line as if over a quiet ocean. The effects of the pollution on the µGrid are analysed in section 4.

2.1.2. Efficiency improvement of low voltage systems based on DC

A high number of the actual loads require a DC voltage at their input [5]. When this DC voltage is obtained from an AC source, two stages are needed in order to transform it: first the AC voltage must be converted into a DC one; then, the DC voltage must be adjusted to the appropriate value. When the voltage source is based on a DC voltage, the consumers can be connected directly through the DC/DC converter, increasing slightly the reliability and the revenues of the system (the power system is simpler to develop since a lower number of converters are required). In these cases in particular – for example where galvanic isolation is required- a more detailed analysis must be performed in order to take into consideration the involved constrains.

However, when consumers operate on an AC field, the converter must be designed in order to connect it to the DC network. It should be taken into account that many of the actual motor drivers are based on a DC intermediate voltage obtained through an AC to DC stage.

When the percentage of DC based domestics loads overcome the 50%, the efficiency of the entire system can be improved if DC voltage is used to support the µGrid. The energy consumed by the Spanish domestic sector during the year 2003 was estimated to be 65683GW·h (the average power was around 7.5 GW in that year) [19]. This consumption is due to DC and AC based loads. The conversion losses when a different voltage infeed is considered are analyzed.

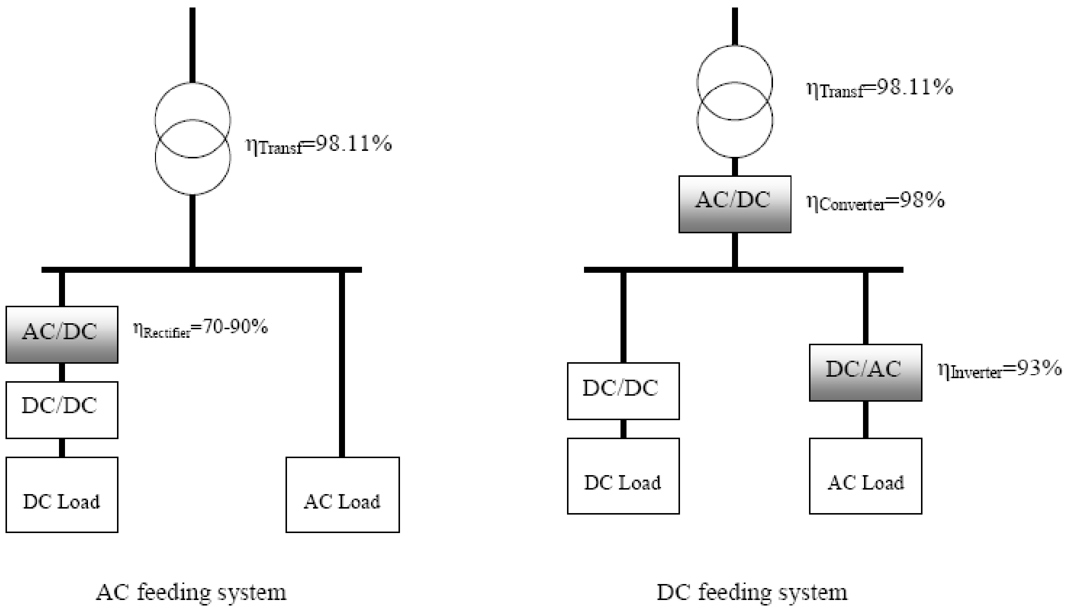


Figure 5: AC feeding system Vs DC feeding system

The efficiency values are obtained from [15], [16], [17] and [18].

The losses associated to the AC feeding system can be formulated as:

Equation 1
$$P_{Domestic} \cdot \frac{DC_{Load}[\%]}{100} \cdot \eta_{Trafo} \cdot (1-\eta_{Rectifier}) + P_{Domestic}(1-\eta_{Trafo}) = P_{LostAC\_feeding}$$

The losses associated to the DC feeding system are:

Equation 2
$$P_{Domestic} \cdot \frac{AC_{Load}[\%]}{100} \cdot \eta_{Trafo} \cdot \eta_{Converter} \cdot (1-\eta_{Inverter}) + P_{Domestic}(1-\eta_{Converter}) = P_{LostDC\_feeding}$$

The DC/DC converter losses are neglected since they are presented on both systems.

If the percentage of the DC consumption on the domestic system is varied between the 30 and the 70 %, the ***difference*** on the power losses between the AC based system and the DC based one can be approximately estimated:

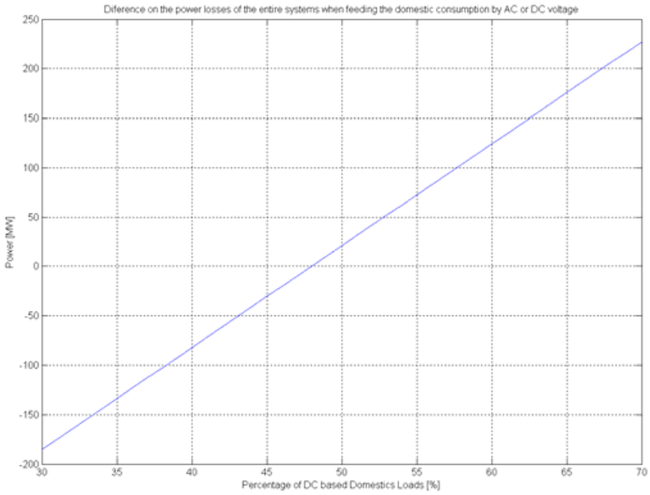


Figure 6: Difference on the mean losses on the domestic sector when DC or AC supplied

As it can be seen, when the percentage of DC based domestic consumption increases above the 50%, savings on energy can be noticeable. When this percentage is close to the 70%, the AC system takes approximately 200MW (over the 2.6% of the active power consumed, or the equivalent to one million tons of CO2 emissions per year) in order to overcome the losses associated to the operation of the converters. Conversely, when the percentage of the load is mainly based on the AC voltage, the efficiency of this alternative can be questioned. However, the domestic consumption is or could be considered as based on DC voltage.

2.2. Another issues related to DC networks

Other advantages regarding low voltage systems based on DC fields are presented next:

- The probability of fault occurrence (caused by lightning, trees, animals, weather conditions…) diminishes when bare overhead conductors are replaced for insulated or underground circuits [9]. In systems based on AC fields, the utilization of these underground conductors is associated to an overloading on the apparent power managed by the entire line (due to its capacitive effect amongst the cables) and to an increase on network investment (due to its high price). However, for systems based on DC fields, the former is fully removed and the later is reduced due to the simplicity on the DC lines (based on a single phase distribution). This is an issue that could be analyzed in systems with high quality and reliability requirements on the energy supply, especially on those processes that usually rely on an UPS system in order to maintain within the voltage limits. The economic evaluation of an underground DC dedicated line might be an alternative option which should be taken into consideration.

- The electrical system is simpler because most of the equipments are based on DC voltages [3], [5]. The control strategy is also simplified to plug & play the resources (avoiding the phase, frequency and magnitude synchronization process) to the network, especially when they are directly generated on DC voltage (photovoltaic sources, wind energy or micro turbines using an intermediate DC voltage, storage systems…).
- The transition to the islanded mode is much faster and reliable than in the AC case. Thereby, the voltage quality can be further ensured.

2.3. Main applications of DC networks

A DC system might be preferred to a conventional 50-Hz AC system in applications where many electronic loads are used, high reliability and power quality are desired and/or low magnetic fields are required. Next, some examples are provided [21]:

- Web hosting, data centres, banks, where reliability is of utmost importance and loads are mostly servers or other computer/electronic equipment,
- Telecom stations, where 48 V DC is already a standard,
- Hospitals, which combine both requirements of low magnetic fields and high reliability,
- Factories with large variable speed drive systems supplied with a common DC source,
- Common office buildings,
- Military applications.

3. Suggested topology and feeding of the DC μGrid

The μGrid must have **at least** one connection point with the main network in order to ensure a high reliability level of the energy supply and the surplus energy delivering. It could be desirable the connection of the converters to different mains in order to increase the overall reliability of the system. This way, each converter should be capable of managing the maximum power rating of the entire μGrid.

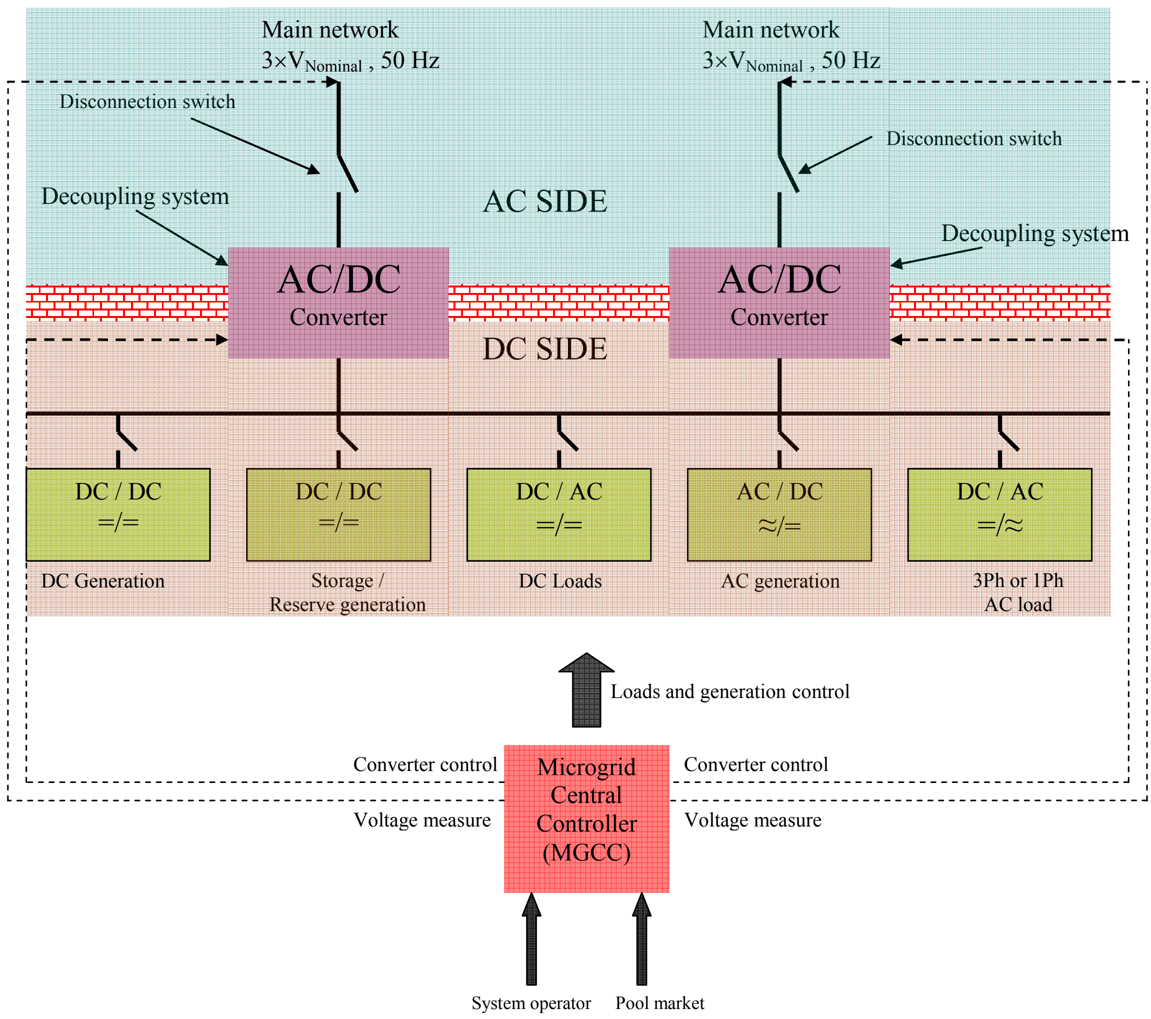


Figure 7: Topology of the μGrid and connection to the main network

The μGrid can be divided into different elements:

- The electronic based bidirectional AC/DC converters which are in charge of connecting the µGrid to the main network and control its inner voltage level,
- Demand: Comprised by all the elements which draw energy,
- Generation: Comprised by all the elements which deliver energy,
- Storage and reserve energy: it contributes to ensure an optimum equilibrium between demand and generation in islanded mode and between the real generation and the generation schedule resulting from the energy market when it is in connected mode,
- The µGrid central controller (MGCC).

The µGrid central controller (MGCC) is in charge of:

- Connecting and disconnecting both networks,
- Dealing with the requirements of the system operator (when this service is provided) or with the pool bounds,
- Synchronizing the entire µGrid as a whole (generation/consumption) in order to improve the revenues of the energy used,
- Ensuring the voltage quality within the entire µGrid, and regulating the final stable point of operation acting as a secondary control.

The primary and secondary control of the µGrid can be split into two different modes depending on whether it is connected or disconnected from the main network.

In connected mode, the balance between generation and demand (inner to the µGrid) is not compulsory since the main network matches it. On this state, other issues can be taken into consideration such as the optimum management on the internal µGrid energy.

However, on the disconnected mode, the equilibrium between generation and demand is mandatory decreasing consequently the freedom on the energy management. In this situation, the MGCC must readjust the consumption and the generation so as to keep the voltage within limits.

3.1. µGrid voltage control in grid-connected mode

In this operation mode, the main converters (the converters connecting the main network with the DC µGrid) are in charge of the ***primary regulation***. However, the MGCC can (or must) be in charge of readjusting it like a ***secondary regulation***.

Traditionally, this voltage control has been performed employing high-speed, hard-wired communication (a master inverter in charge of controlling the operation of the other inverters through a separate communication network). Despite allowing expandability in localized systems, it is not appropriate for the interconnection of multiple systems without requiring a considerable reconfiguration of the components and the communication network. Besides, this system concept has little redundancy because it is completely reliant on the operation of the master unit [20]. A better alternative is a multi-mastered primary voltage control.

A power-voltage droop control is a voltage control which guarantees that the voltage regulation is performed by every converter connected to the network [4]. In this control, the power driven by the DC network depends exclusively on the µGrid voltage. This kind of control is only useful when there are at least two converters supplying energy to the µGrid; if there is only one converter for the voltage regulation, a constant voltage control is the most appropriate solution.

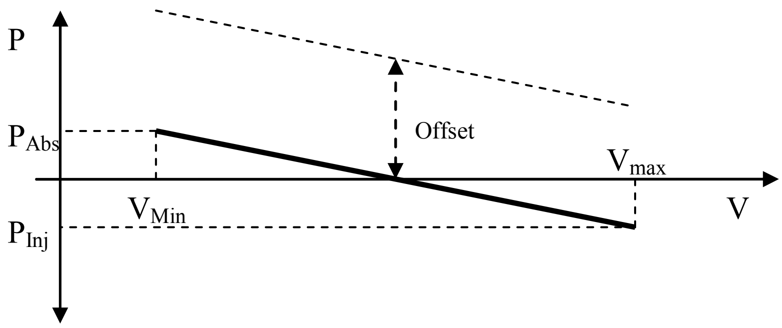


Figure 8: Droop control

The voltage and the power are related by the following expression:

Equation 3

$$P_{Output} = \frac{P_{Inj} - P_{Abs}}{V_{Max} - V_{Min}} \cdot \left(V_{DC} - \left(\frac{V_{Max} + V_{Min}}{2} \right) \right) + Offset$$

V_{DC} is the actual voltage of the network and the only variable on the equation.

The DC voltage at the coupling point is measured and introduced on the Equation 3 in order to learn the amount of power the converter must deal with. This method ensures that every converter shares the power of the whole µGrid.

The offset belongs exclusively to the ***secondary regulation*** implemented in the MGCC. Through this variable, the grid voltage can be re-established to the appropriate level independently of the active power value.

A constraint that arises from the droop control is the mismatch of the shared power when the resistances that couple the converters to the µGrid differ. If this occurs, both converters are bounded to operate on a different point of their droop characteristic.

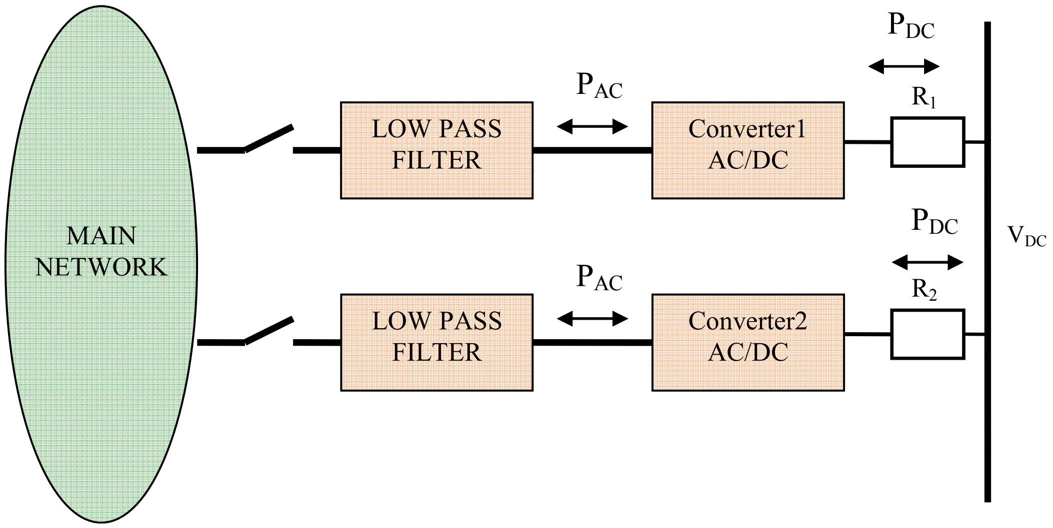


Figure 9: Different connection features of the supplier converters

In Figure 10 it can be seen how the operation point of the converters varies when they are separated from the µGrid by different resistances. It can be observed the **difference** on the amount of power injected by the converters (in percentage of the nominal power) when the resistance that separates them from the common coupling point varies (as percentage of the base impedance). The base values are V=230 Volts and P=10kW.

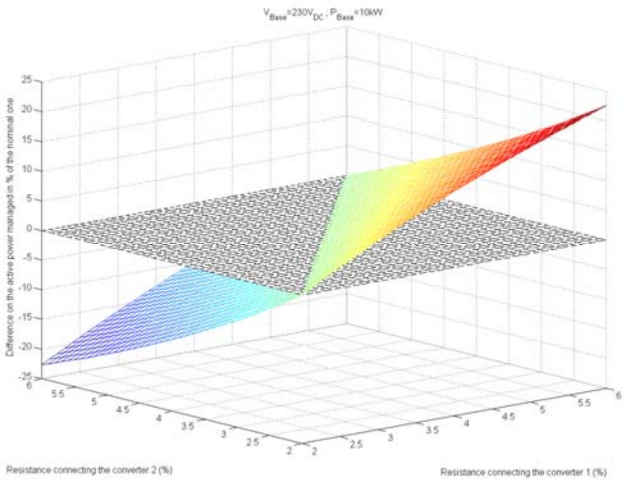


Figure 10: Difference on the power injected by several inverters connected through unequal resistances

A solution for this problem could be the introduction of the line resistance in the algorithms in order to balance the power sharing.

3.1.1. Simulations

In this section, several simulations of the µGrid primary voltage control when the droop characteristic is implemented on the converters are shown. These simulations are executed based on the scheme shown in Figure 11:

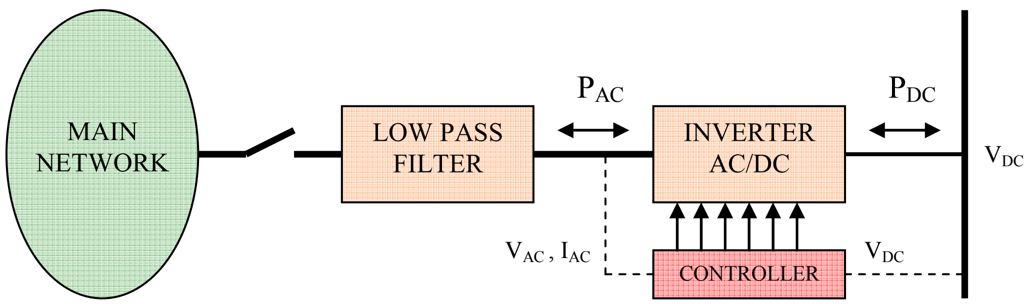


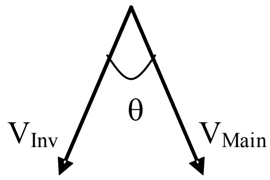
Figure 11: Inverter based converter connection

The AC to DC conversion and the control of the power flow (related to the DC voltage through the droop characteristic of Figure 8) are simulated as inverter based technologies. The advantages of this kind of converters in comparison to the converters based on the rectifier technology are the following ones (this is applicable to low power rating networks up to a few MW):

- Bidirectional power flow,

- Reactive power regulation on the AC side (ancillary services),
- Limitation of the emitted harmonics into the AC system,
- Capability to draw power from the AC system even when a voltage drop happens.

The power injected or absorbed from the main network is regulated through the sinusoidal voltage of the inverter. Supposing an inductance of X_L which separates the inverter from the main network, it is possible to control the power that flows from one to the other through the variation of the angle which separates their voltage vectors as:



Equation 4

$$P = \frac{V_{Inv} \cdot V_{Main}}{X_L} \sin(\theta)$$

This angle is related to the µGrid voltage through the droop characteristic as it is shown in Figure 12 (V_{AC} is the inverter voltage):

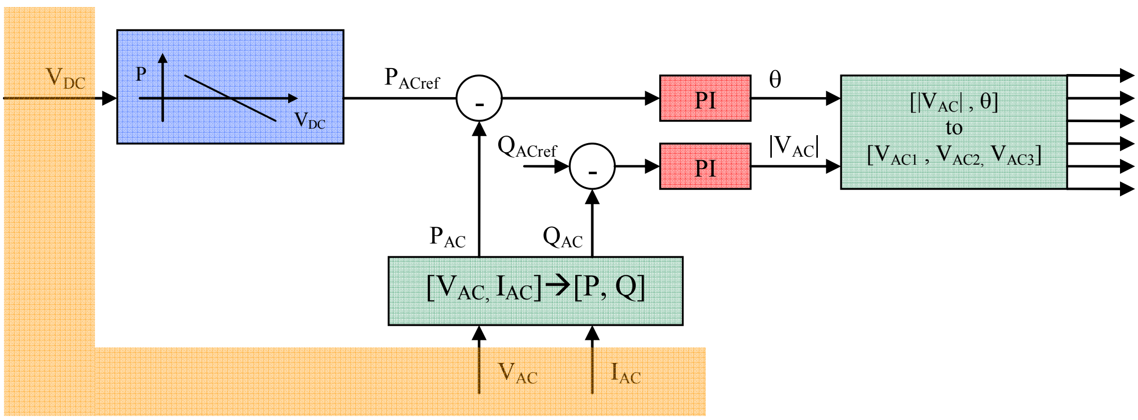


Figure 12: Voltage of the µGrid control

In order to control the active and reactive power, the voltage on the DC side and the current and voltage on the AC side are measured. From the droop characteristic, the active power reference is obtained in order to compare it with the real one. As a function of the resulting error, the angle of the AC voltage is varied. The error on the reactive power in comparison with the measurement will define the magnitude of the inverter AC voltage.

This control algorithm is simulated when two converters are feeding a μGrid with a P_{Base}=10kW and a voltage base of V_{DC_BASE}=230V.

The load is supposed to take a value of 0.5 p.u. up to t=0.5seconds, then, its value changes to 1 p.u. returning to 0.5 p.u. 0.5 seconds later.

The droop voltage on Figure 8 is considered to have the following values:

P_{Abs}=10kW, P_{Inj}=10kW, V_{Max}=240V, V_{Min}=220V. Not secondary control (Offset control) is implemented.

Two different cases are simulated:

a) The resistances connecting the inverters to the network (Figure 9) are equal taking a value of 2%,

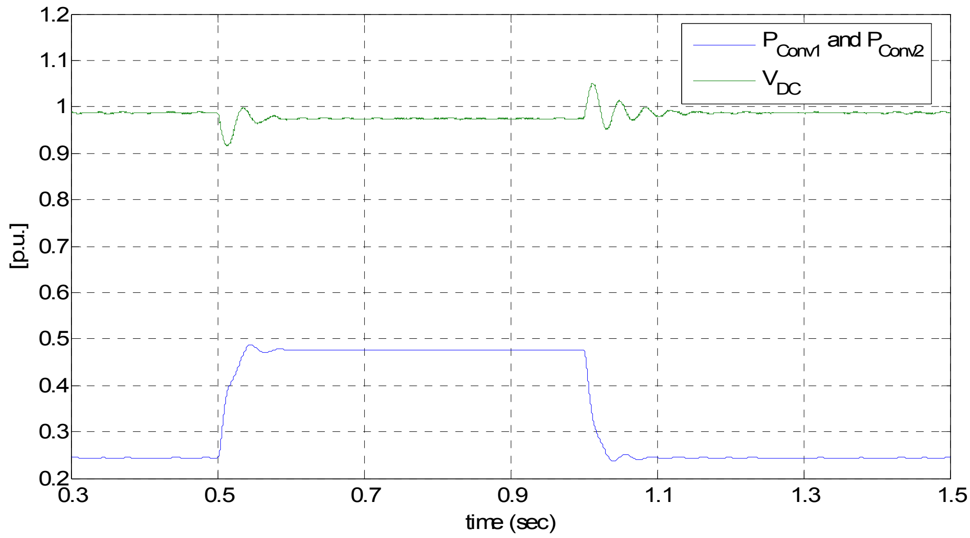


Figure 13: Equal resistance separating the converters from the μGrid

It can be seen how the active power is uniformly distributed between the two converters. As the power output increases, the DC voltage decreases in order to comply with the drop characteristic.

b) The resistances connecting the inverters to the network are different taking the following values: R_{Conv1}=2%; R_{Conv2}=5.29%.

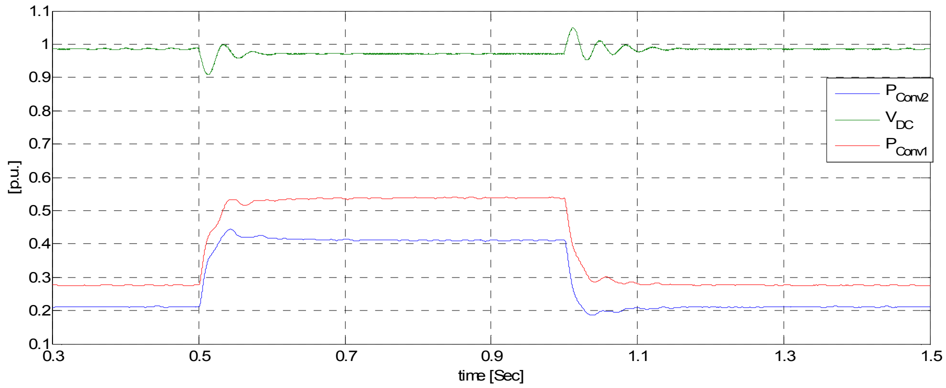


Figure 14: Different resistance separating each converter from network

In this case, the power is not uniformly distributed between the two converters. The difference in the active power managed is approximately of the 15%, as it was expected from Figure 10.

This method achieves a primary regulation over the entire DC network voltage. In case of a significant variation of its magnitude from the nominal value or a great disequilibrium between the power leading each converter, it should be taken into account that the MGCC can displace the operating point of each converter through the OFFSET values so as to re-adjust the active power supply.

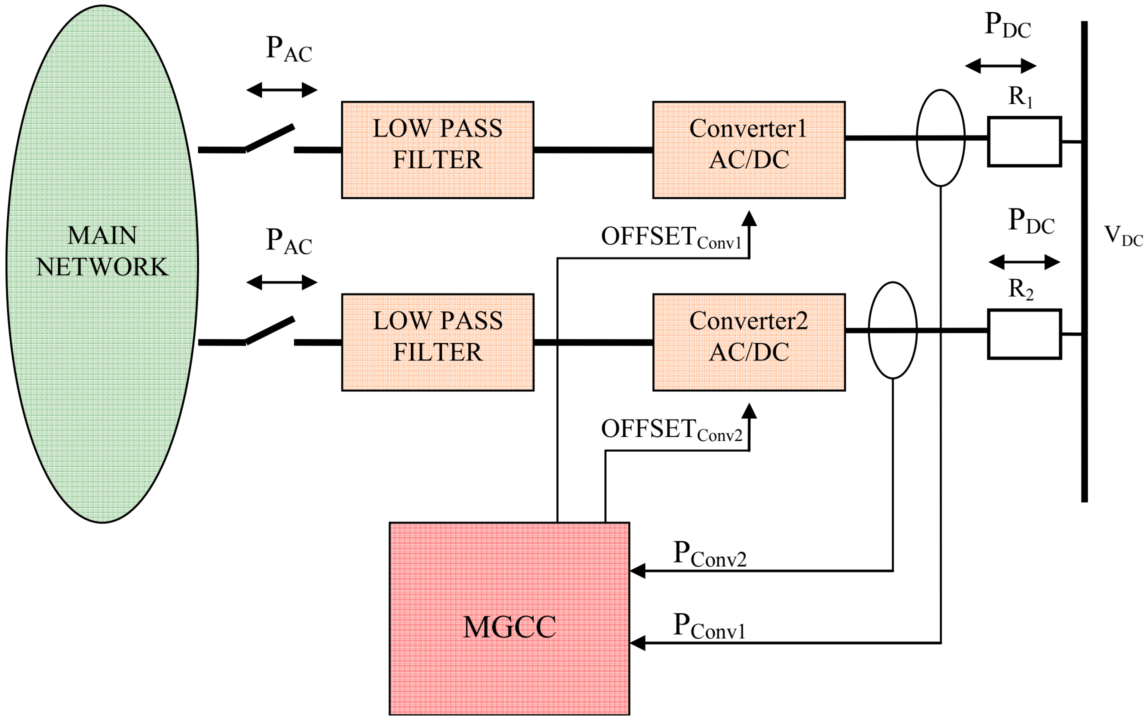


Figure 15: Equalization of the active power amongst the converters.

A very simple method for performing it is an Integral based controller in charge of minimizing the different power leading of each converter. This PI output method adjusts the OFFSET variable directly (Figure 15 and Figure 16).

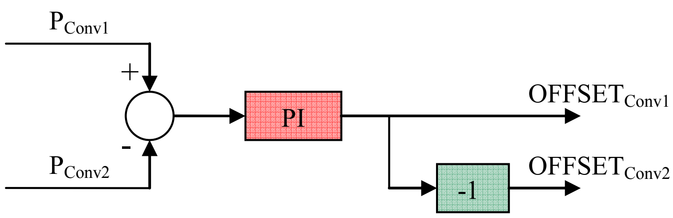


Figure 16: PI control of the active power mismatched

In Figure 17 it can be seen the same case as stated before (Figure 14), when the OFFSET control is implemented.

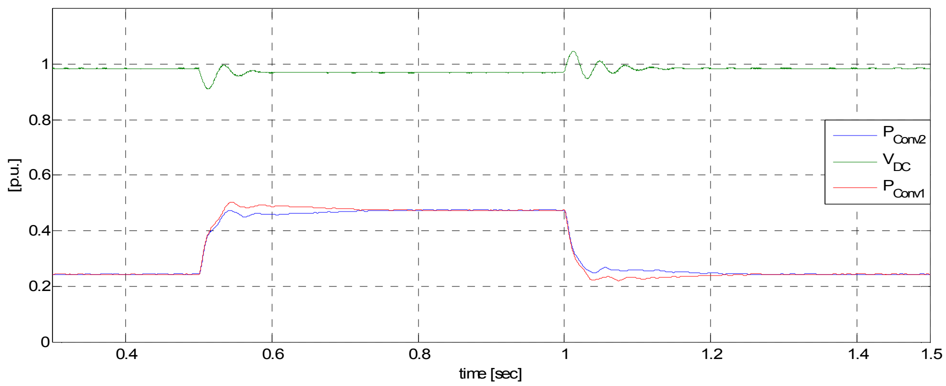


Figure 17: Power equalization through the offset control

The active power is successfully re-adjusted between the converters. For this purpose, the OFFSET variable is oppositely changed in the converters as it is shown in Figure 18:

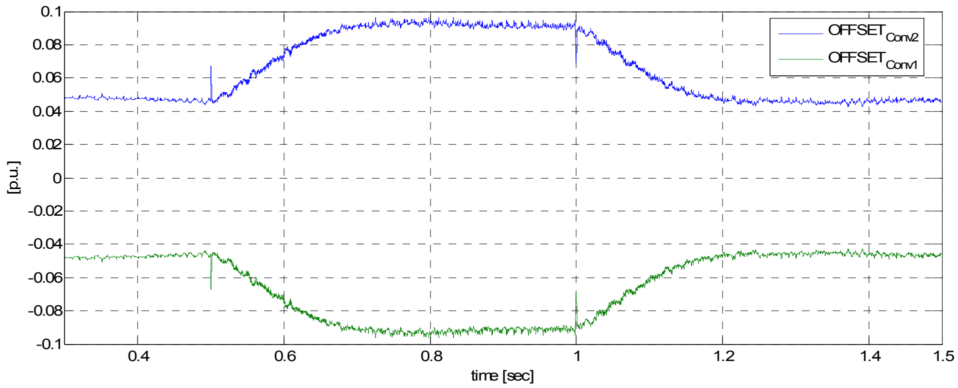


Figure 18: Offset variation

Using this simple control strategy, the voltage of the entire µGrid is precisely readjusted when the power is shared by the converters.

This primary and secondary control ensures the establishment of the correct voltage in the µGrid when the converters are performing the connection of both networks.

3.1.2. Voltage control during voltage perturbations on the main network

When a voltage perturbation occurs outside the µGrid, its propagation into the µGrid is partially limited by the converter that decouples both networks.

It is possible to remain connected to the main network even when its voltage is out of the nominal limits (absorbing energy or helping to the main network through the active or reactive power injection). This produces an increase on the reliability level of the µGrid.

On figures below, the capabilities of the inverter based converters to control the power flow even when the voltage of one of the feeders drops are presented.

The simulations are based on the schemas provided in Figure 11 and Figure 12 supposing that the resistances between the converters and the loads take the same values.

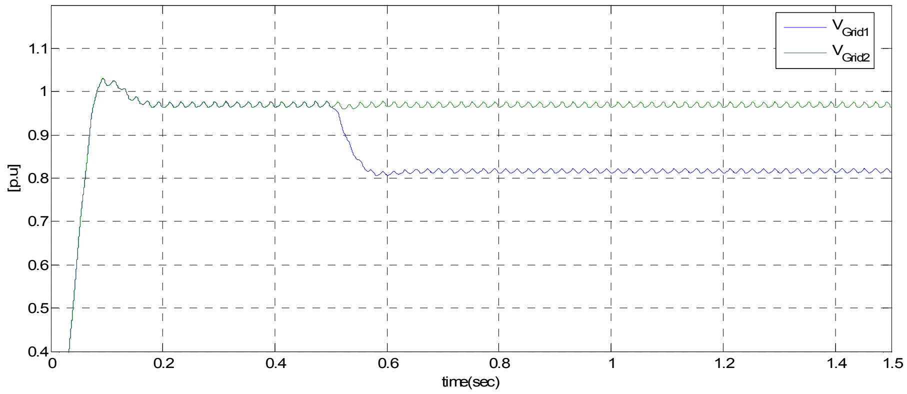


Figure 19: Voltage drop on the AC side of converter 1

As it was shown in Figure 12, in order to regulate the power flow between the two systems, the angle between the network and the inverter voltage must be controlled.

It can be seen how the converter 1 grows up the angle in order to increase the active power absorption when its voltage drops.

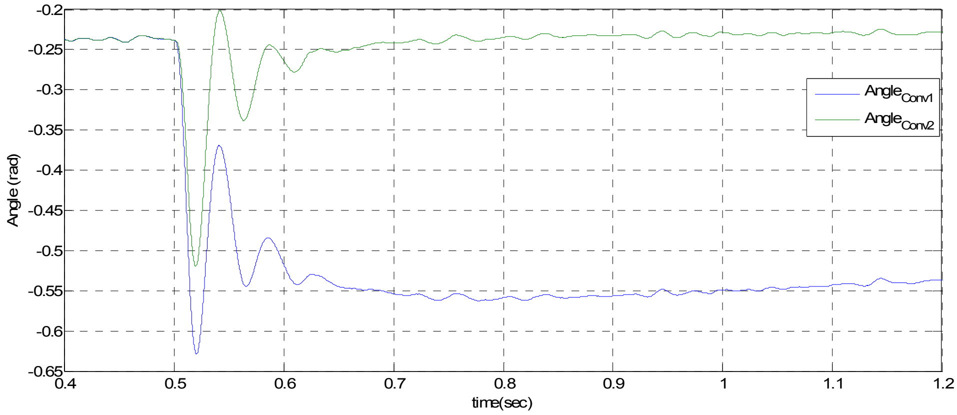


Figure 20: Angle control of each converter

Figure 21 shows the active power managed by the converters. It can be observed how after a transition time, the power balance is reached again.

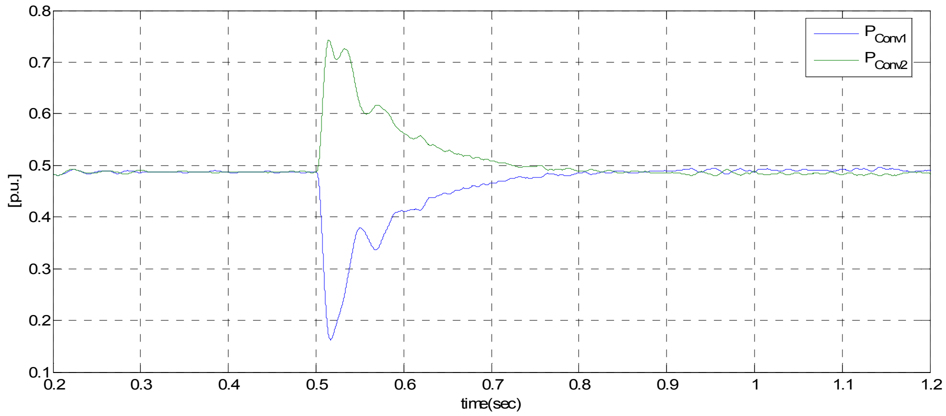


Figure 21: Active power managed by each converter

Anyway, the voltage on the DC side of the converter (the µGrid voltage), is kept stable. It can be noticed that the variation of the PI parameters of the controller or the type of controller contributes to decrease the overshooting.

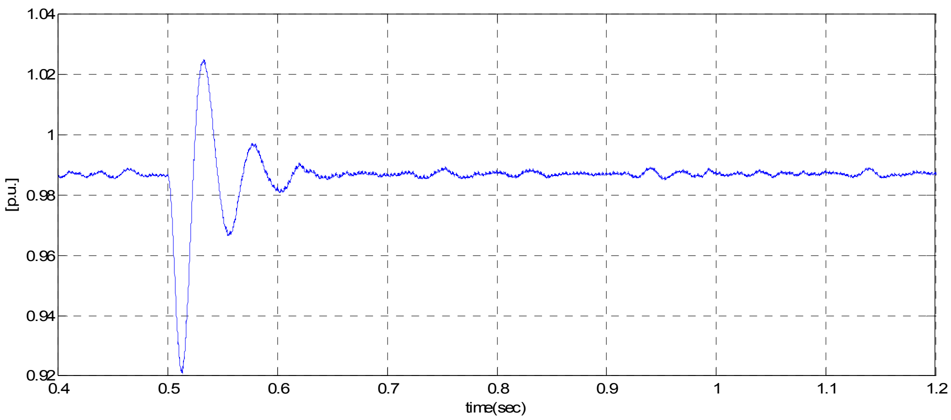


Figure 22: Voltage on the DC side

Despite the fact that the µGrid can be connected to the main network interchanging power even when a distorted voltage on the main side occurs, it could be necessary the transition to the islanded mode and the wait until the AC voltage recovers the nominal value.

3.2. Transition to islanded mode

The µGrid can operate in islanded mode when it is necessary. This situation could be, for example, required when there is a lack of quality of supply on the main network. In this chapter, a controlled transition to the islanded mode is described.

There are three different states which must be considered individually:

- the disconnection of both systems,
- the operation in islanded mode,
- the reconnection to the main network.

3.2.1. Disconnection of the systems

The voltage variation showed on chapter 3.1.2 contributes to the disconnection of the µGrid from the main network and consequently to the transition to the islanded mode.

When the MGCC decides that the disconnection is necessary, the two main converters start decreasing of their power injection slowly. This action can be performed through the offset control or autonomously. The internal generation of the µGrid starts its operation when the measured voltage of the µGrid falls below a threshold value. In order to increase the redundancy, the MGCC sends a signal to the µGrid generator so as to command it the transition to the islanded state (Figure 23).

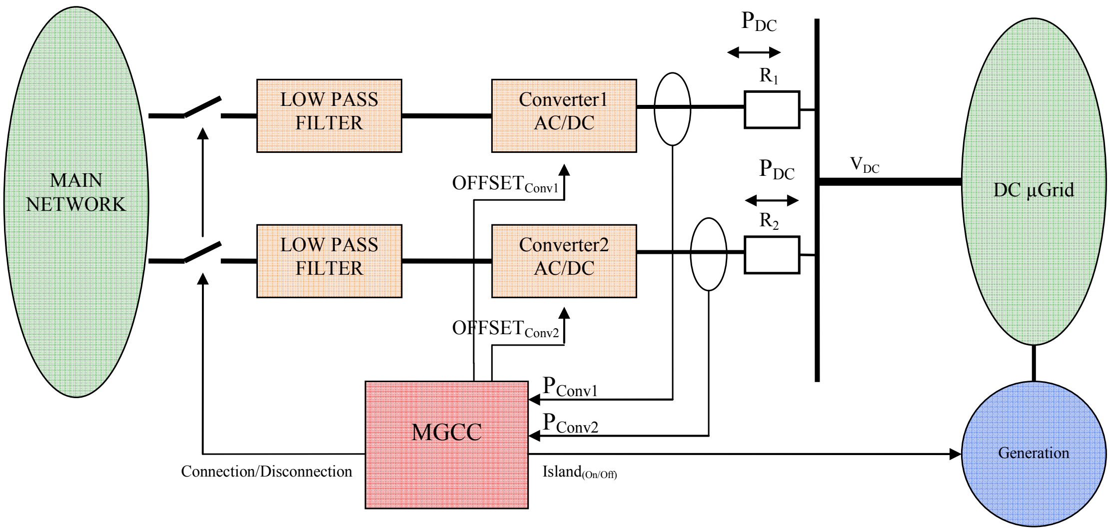


Figure 23: Transition to islanded mode

The following figure shows the control of the main converters in order to reduce their power injection down to zero:

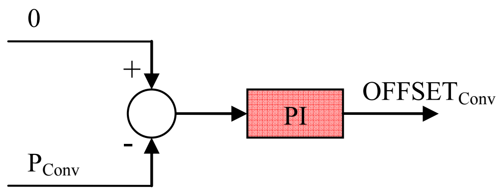


Figure 24: PI control to null the active power of the main converters

The generators connected to the µGrid are in charge of supporting the DC voltage when it comes below the threshold value. In this chapter, some simulations regarding this issue are presented. In such simulations, it has been considered that the threshold takes a value of 0.956 p.u. (220 V_{DC}). When this lower limit is exceeded, the generation in the µGrid starts it operation in order to face the voltage drop automatically.

This generation requires the management of a DC/DC converter in charge of regulating the injected power (see section 7.1.2).

The control scheme is shown in Figure 25:

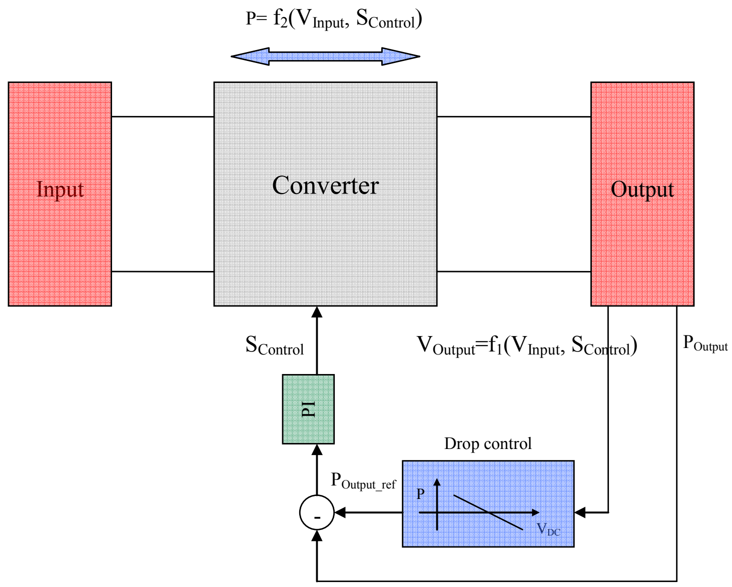


Figure 25: Primary voltage control of the µGrid in islanded mode

The voltage within the network is measured and tested into the droop characteristic in order to obtain the reference active power to be injected. A PI control is accomplished over the resulting error and the DC/DC converter controlled from it.

At t=0.5sec., a voltage drop on the AC main network is detected (as on chapter 3.1.2). The two main converters are able to maintain the voltage in the μGrid within limits. At t=1sec, the MGCC sends the command to turn the μGrid to the islanded mode. As the DC voltage drops below the threshold limit, the internal generation/storage contributes to support the DC voltage.

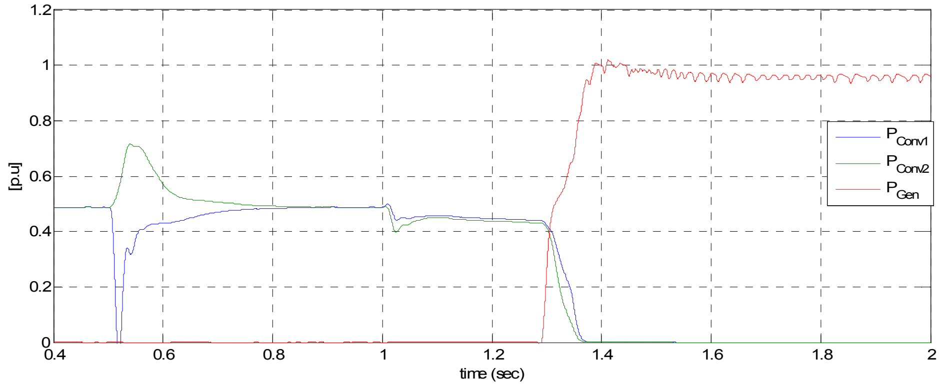


Figure 26: Distribution between the external and internal active power to guarantee the DC voltage re-establishment

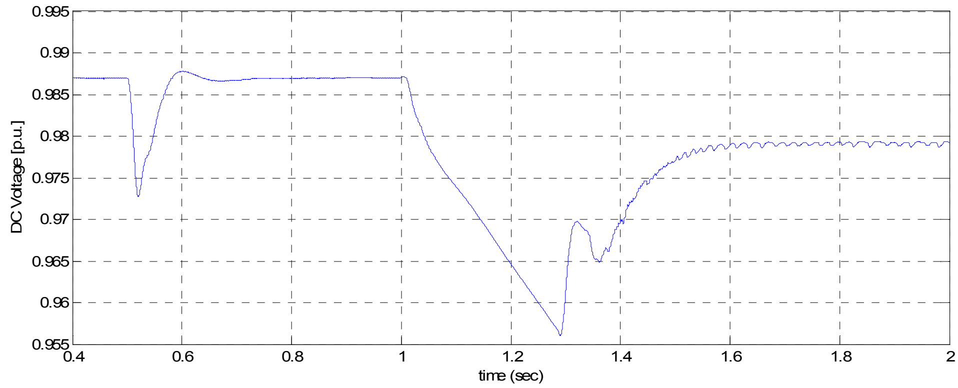


Figure 27: DC μGrid voltage

Figure 26 and Figure 27 show the results of the simulations. As it can be seen, the voltage is kept within the nominal values when the voltage drops on the AC side. From t=1sec onwards, the two main converters reduce their injected power, decreasing as a result, the voltage. When the voltage magnitude reaches the established threshold of 0.956 p.u, the internal generators are required to participate in the voltage support injecting active power accordingly to their droop characteristic (in this simulation, it has been considered that both converters have the same droop curves).

Since the droop characteristic is the same for both converters, the stability value of the voltage in the islanded operation mode (on the simulations only one converter controls the voltage) is lower than the corresponding one to the grid-connected operation mode where the power is distributed between both converters.

Due to the fact that most of the converters connected to the system have a capacitor at the output stage that operates as an inherent storage, the transition to the islanded mode is softer on the DC networks.

An additional strategy to cope with the generation-consumption balance in the islanded mode and/or the transition process between the grid-connected and the islanded states is the implementation of a load shedding scheme that operates in a similar way as the storage primary control.

3.2.1.1. Operation in islanded mode

There are two additional modes of detecting the islanded mode in a DC network. On the one hand, the MGCC can inform the entire network at the right moment sending for this purpose, a disconnection signal to the main converters. On the other hand, each system connected to the µGrid can detect the voltage at the PCC (Point of Common Coupling) and change to the islanded mode if this voltage is out of the pre-established limits (see section 3.2.1). Once the islanded mode is reached, the suppliers in the islanded network must deal with the voltage control of the µGrid since the main converters are not already feeding it. As the equilibrium has to be maintained by many low rated generators supplying a small fraction of the total active power, the synchronization process based on a DC voltage is quite simpler because the frequency and phase synchronization constraints associated with AC networks are overcome.

A single way of communication among every source is established through the voltage level of the µGrid ensuring that the entire system operates as a whole.

On low voltage AC networks, a problem might appear when the total energy coming from dispersed generation sources has to be coordinated because neither the frequency nor the voltage magnitude is directly related to the active or reactive power (the R/X ratio of the line impedance is neither predominantly resistive nor inductive).

In islanded mode, the MGCC has the great responsibility of ensuring that the active power balance is correctly reached (whatever the optimum is) without affecting the quality of supply of the µGrid. This can be performed through the appropriate connection/disconnection of the generators and loads (charging storage, dispensable loads…) or through the modification of their set points.

The µGrid sources could be classified into three different groups:

- Non renewable generation (NRG); the primary energy source of these generators can be stored when it is not being used,
- Renewable Generation (RG); this kind of generators should have the priority on the coupling because there is no control of the primary energy,
- Storage: there is the possibility of recovering it through the consumption of the stored energy.

The RG is always connected to the system injecting its available energy. The remaining energy resources (NRG and storage) implement a droop control method in order to satisfy the power demand.

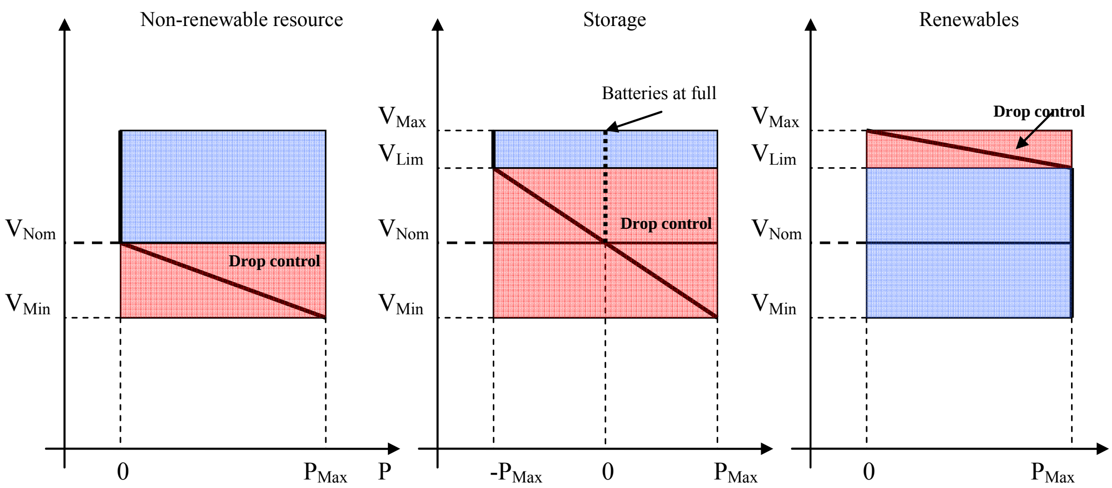


Figure 28: Voltage control in a DC islanded µGrid

The NRG and the storage devices are in charge of detecting when the voltage in the µGrid falls below a minimum allowable limit for the correct operation of the system (V_{Min}). When this occurs, they have to start their operation according to their droop characteristics so as to participate on the voltage control.

The storage devices consume or generate the required amount of energy so as to achieve the active power balance inside the μGrid.

In order to maximize the system efficiency, the RG is continuously delivering power to the network. However, when the load consumption inside the μGrid decreases, the voltage on the network might exceed the acceptable voltage limit. In that situation, the RG will have to decrease the power injection in order not to overload the μGrid (for instance, with a droop characteristic).

Every droop characteristic is susceptible of being altered by the MGCC's control through the OFFSET variation (Figure 8). Each OFFSET must be appropriately managed in order to optimize the available energy within the μGRID all the time and to keep the voltage level within safety limits (Figure 29).

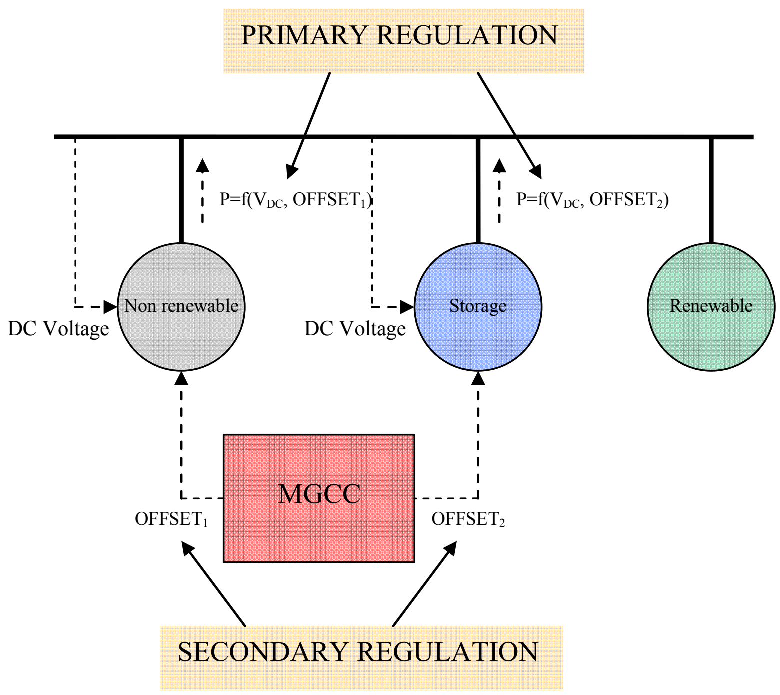


Figure 29: Voltage control in islanded mode

It must be noted that the MGCC can also readjust the energy demand through the suitable connection or disconnection of the loads.

3.2.2. Reconnection to the main network

Once the voltage on the AC network has reached its nominal value, both systems are reconnected again in order to operate in the normal grid-connected mode.

The following simulation shows a voltage variation on the AC side of the first main converter lasting from 1 to 1.5 seconds and 0.2 p.u depth. Initially, both converters readjust their voltage angle in order to maintain the power injection into the µGrid. At t=1.5 sec, the MGCC sends the order for transition to the islanded mode. When this occurs, the voltage on the AC side is recovered. Finally, at t=2 sec, a new command is sent with the objective of reconnecting the µGrid to the network.

The voltage on the mains supplying the µGrid is shown in the following figure:

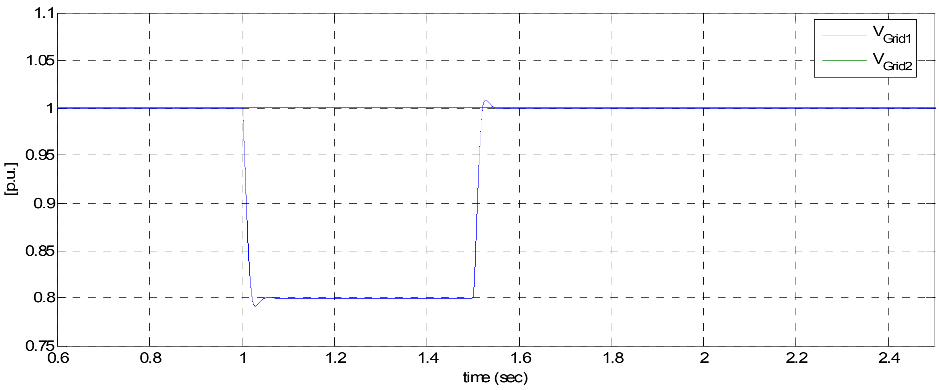


Figure 30: AC voltage on the main side

When the voltage drop on the AC side occurs, the two main converters adapt themselves in order to readjust the active powers. After receiving the command of transition to the islanded mode, both converters reduce their power injection taking the generators of the µGrid the voltage control responsibility for the entire µGrid. At t=2sec, the MGCC sends the reconnection signal. It can be seen how the active power is shared between the converters and the generators in the µGrid.

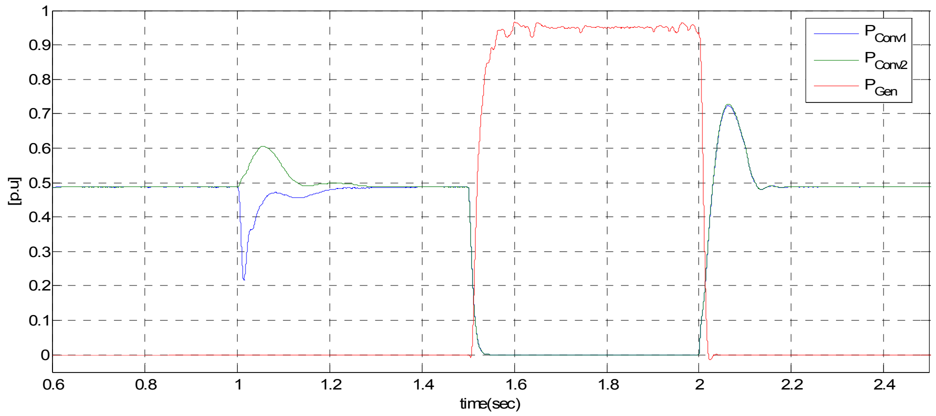


Figure 31: Power distribution between converters and internal generation

The µGrid voltage variation can be seen in **Figure 32**. It is shown how the voltage value does not have a significant deviation from its nominal value. It can be noticed that an accurate control is achieved within the DC voltage through the employment of a very simple strategy.

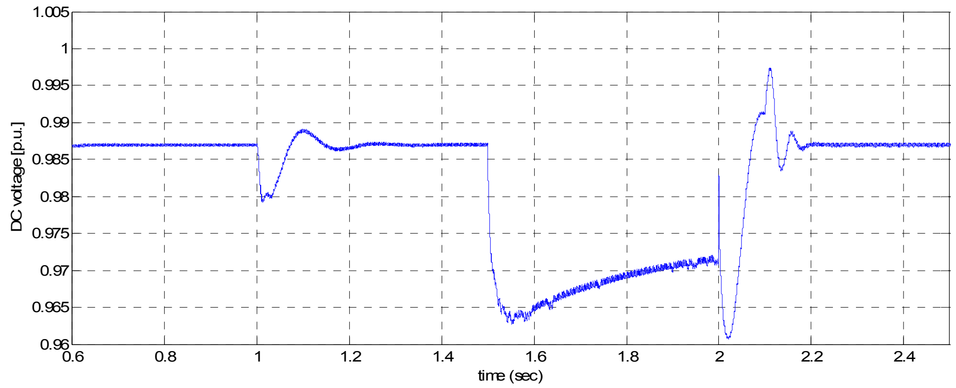


Figure 32: DC voltage within the network

3.3. Voltage on DC based networks

An important issue regarding DC networks is deciding the most appropriate voltage that will feed them.

If the actual infrastructure of the AC system is considered to be unalterable, the maximum allowable voltage on a DC based system is, at least, the peak to peak value of the phase to phase voltage. This restriction is due to the cable insulation that is only capable of supporting that voltage.

It order to analyse a DC voltage system, it can be assumed that the losses remain the same when the AC low voltage system is fed with DC.

Let's consider two networks. The first one is based on a conventional AC system and the second one on a DC system. In both cases, the same line resistances are considered.

On the AC system, the losses associated to the energy distribution are the following ones (neglecting the neutral conductor):

Equation 5 $$P_{Loss\_AC} = 3 \cdot R_{Line} \cdot I_{RMS}^2$$

Equation 6 $$I_{RMS} = \frac{S_{AC}}{\sqrt{3} \cdot V_{AC}}$$

From Equation 5 and Equation 6:

Equation 7 $$P_{Loss\_AC} = R_{Line} \cdot \frac{{S_{AC}}^2}{V_{AC}^2}$$

On a DC system, the losses on the distribution process are:

Equation 8 $$P_{Loss\_DC} = 2 \cdot R_{Line} \cdot I_{DC}^2$$

Equation 9 $$I_{DC} = \frac{P_{DC}}{V_{DC}}$$

From Equation 8 and Equation 9:

Equation 10 $$P_{Loss\_DC} = 2 \cdot R_{Line} \cdot \frac{{P_{DC}}^2}{V_{DC}^2}$$

Comparing both losses (Equation 7 and Equation 10):

Equation 11 $$R_{Line} \cdot \frac{{S_{AC}}^2}{V_{AC}^2} = 2 \cdot R_{Line} \cdot \frac{{P_{DC}}^2}{V_{DC}^2}$$

Consequently, the equivalent DC voltage can be expressed as follows:

Equation 12 $$V_{DC} = \sqrt{2} \cdot V_{AC} \cdot \frac{P_{DC}}{S_{AC}}$$

Assuming that the same active power is transmitted over both lines, the equivalent voltage is:

Equation 13 $$V_{DC} = V_{AC} \cdot \cos(\theta)$$

The equivalent voltage on the DC network is calculated in order to maintain the same losses as the corresponding one in the AC system. It can be noticed that this voltage is within the limits of the isolation.

As the power factor on the load is less than 1, the advantages of the DC system are more appreciable. It should be taken into account that, in the DC case, the LV distribution network requires two cables instead of three (of even four) compared to the conventional AC system.

If the actual infrastructure of the AC system (based on four cables) were to be used to distribute power through a DC voltage (with the magnitude proposed on Equation 13) the delivered power could be doubled without overcoming the losses associated to the AC system.

Other considerations and voltages are surveyed in the literature. In [5] the advantages and disadvantages of several DC voltage values are analyzed. In [3] a voltage range between 400 and 600 volts is proposed to feed DC networks with ratings from 10 to 100kW.

In [21] a voltage level of 230-300 Volts is proposed.

In [5], several voltages levels that vary from 48 to 230V are analyzed, providing the corresponding advantages ad disadvantages

Nowadays there are available modules based on IGBT which can manage power in the range of 1 MW, with a DC voltage higher than 1kV [11] [12]. Consequently, there is no contradiction with the previously presented information.

3.4. Ground coupling on the µGrid

It is important to provide the µGrid with a ground reference that contributes to ensure the correct protection schemes, and to improve the security on the direct contacts.

On the main converters, this ground reference is obtained if the inverter is coupled to the network through a decoupling transformer. Afterwards, the DC part of the converter must be firmly grounded.

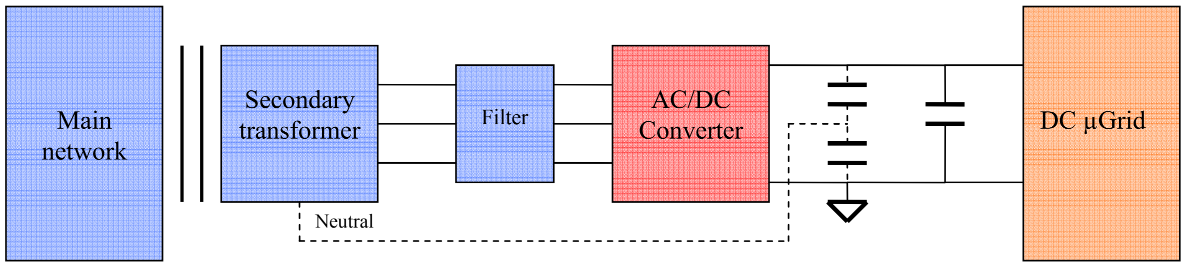


Figure 33: µGrid isolation through a decoupling transformer on the AC side

Another option that ensures the ground reference is to connect directly the converter to the AC mains and isolate the DC side of the converter connected to the µGrid from the DC side of the converter connected to the network through a DC/DC converter based on a transformer coupling (fly-back converter, push-pull converter…).

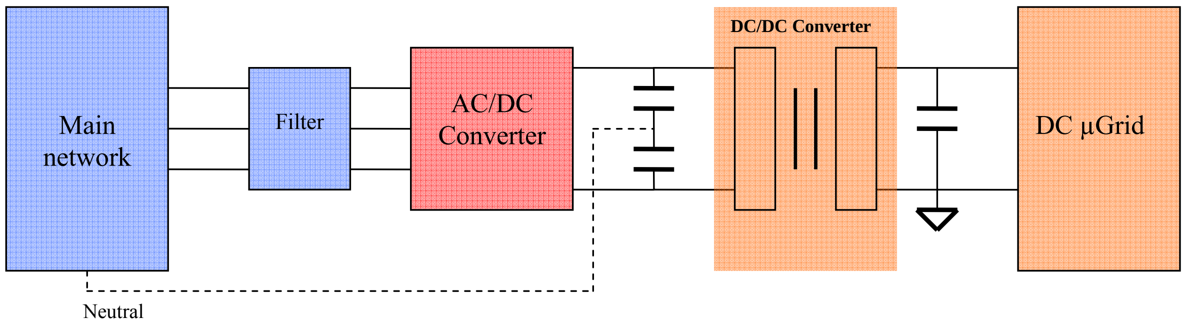


Figure 34: µGrid isolation through a decoupling transformer on the DC side

In the dashed line, the connection of the neutral wire is available for different IGBT commutation types (i.e. PWM switching).This ground reference will be the reference for any resource coupled to the µGrid.

When the generator (or the load) is prepared to operate on its own ground reference, the resource can be islanded from the network through a DC/DC converter (Figure 34), or through a transformer on the case of AC resources (Figure 33).

3.5. Breakers operating on a DC based system

Every system connected to the µGrid, generation or consumption, should be able to disconnect itself from the network when a fault occurs.

Due to the low ratings of the generators connected to the network, the short circuit current in the µGrid is reduced in comparison with the typical network. Even when the µGrid is connected to the mains, the short circuit power is highly limited by the two main converters that feed it.

Therefore, under fault conditions, the voltage on a wide area around the fault location is affected. As a result, generators and loads connected close to the fault are influenced by the voltage drop.

Although all devices are connected to the DC network through electronic systems which ensure a fast response to over-currents and increase the redundancy and safety of the system, breaker schemes are also installed.

The short-circuit current cut off when DC is used has been traditionally hindered by the absence of the current zero crossing. However, nowadays there are low voltage breakers capable of getting connected and disconnected even under strong current conditions [1].

Figure 35 illustrates a typical time-current tripping characteristic for a thermal-magnetic circuit breaker. Usually, manufacturers provide the AC curves at the standard frequency and some scale factors so as to convert such curves for DC applications.

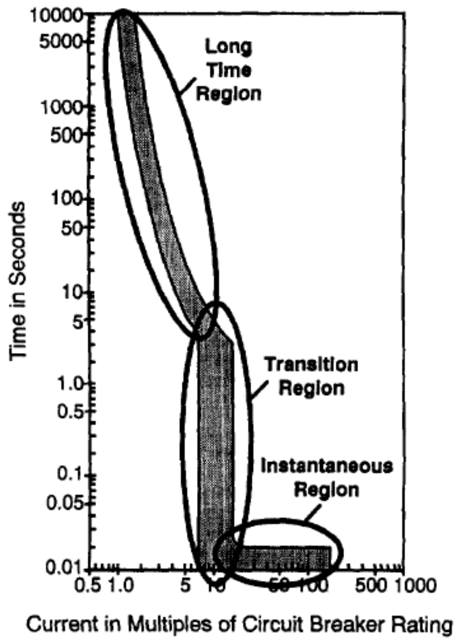


Figure 35: Typical time-current tripping characteristic for a thermal-magnetic circuit breaker

The long-time delay region generally covers currents from 100% of rated current to the designed instantaneous trip. In most cases, the long time upper level is approximately the 500% of the rated current. The sensing element for the thermal-magnetic circuit breaker in this region is a bimetal. This bimetal is heated by the current flowing through the circuit breaker. Deflection is proportional to I^2 so that it is an ideal RMS current sensor. Deflection with DC is the same as the corresponding one to the RMS value of AC, thus, the time current characteristic is the same for both, AC and DC, in the long time delay region.

Manufacturers generally provide adjustments to the trip curves in the transition employing multipliers or redrawn AC trip curves. The effect of these adjustments is a slightly increase on the stated AC magnetic tripping levels when the same circuit breaker is used in DC circuits as indicated in Figure 36. Some manufacturers express this difference as a multiplying factor that varies from 1.1 to 1.4 times the AC tripping current for DC applications. Other manufacturers provide circuit breakers with special magnetic trip levels designed below the standard ones being specially intended for protection of batteries against sustained overloads.

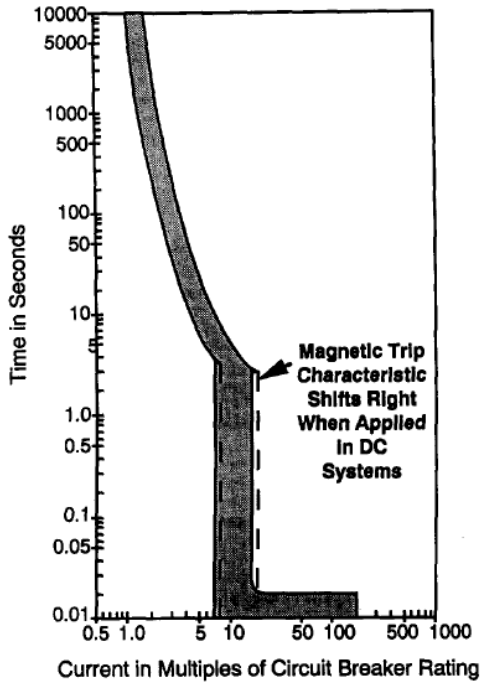


Figure 36: Characteristic curve for a thermal-magnetic circuit breaker modified for DC applications

On the instantaneous region, the clearing time of the actual circuit breakers varies as a function of the type of circuit (AC or DC) and the design of the interruption system of the circuit breaker.

Many designs, especially in current limiting circuit breakers, force an early current zero and consequently, under short-circuit conditions, they do not wait until the normal sine wave period. For these devices, it is irrelevant whether the circuit is AC or DC, since interruption is initiated and carried through during the initial upswing of the fault current. Yet, the rate of rise or shape of the transient current has a significant influence on the capability of mechanical and electrical systems within the circuit breaker to cause interruption.

Low voltage power circuit breakers (LVPCB) for application in DC systems are evaluated and rated under ANSI C37.14, C37.16 and C37.17.

Further information about circuit-breakers operating with DC currents can be obtained from [13] and [14].

4. Quality of supply in the µGrid

As it was mentioned on chapter 2, the AC network is isolated through the main converter from the current pollution -harmonics- produced by the non-linear and reactive loads. This pollution is confined into the µGrid, where it is easier to regulate.

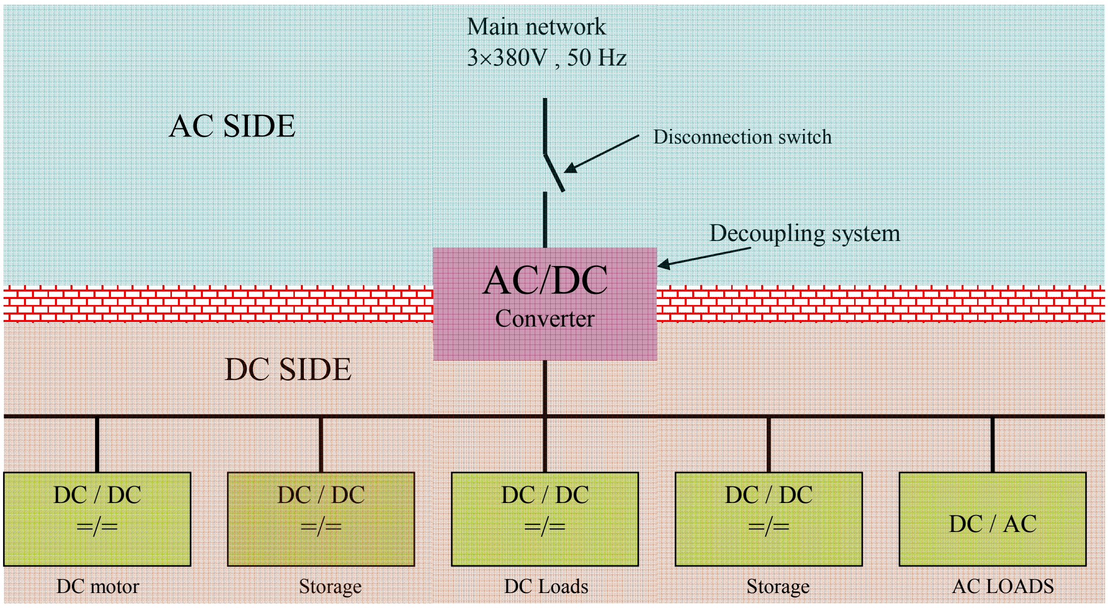


Figure 37: Load isolation through the AC/DC converter

Within the DC network, the emitted harmonics are produced by the active power oscillation of loads and generators.

The energy obtained from renewable energy resources (wind energy, solar energy…) has an intermittent nature. Some loads can also present a variable response. The oscillation of the active power generated or consumed in the µGrid causes voltage changes due to the direct relation between the voltage and the active power through the droop characteristic.

The advantage of the DC network is on the capacity to decrease this voltage effect through the connection of distributed capacitors in the line that are able to filter out the voltage fluctuations.

It is unlikely to connect any load to the DC network without a previous DC/DC converter (or a DC/AC converter) that adjusts the voltage and filters it. The most common DC/DC converter is based on a second order filter plus a switch in charge of modulating the input energy (see chapter 7.1). On its input stage there is always a capacitor which ensures an inherent storage characteristic which also contributes to flatten the voltage oscillations within the network.

In case of AC loads or sources, the DC stage capacitor contributes to the reactive power needs. It is also worth mentioning that single phase loads and unbalanced loads would lead to generate harmonics on the DC bus (see [7] and [8]).

5. Conclusions

The DC based µGrid has demonstrated to be a challenging alternative for the increasing necessity of bundling the dispersed generation as a bigger and more controllable equivalent producer / consumer.

The application of the µGrid concept has the following advantages:

- Improvement of the energy efficiency, reduction of the overall energy consumption due to the local generation, reduction of the environmental impact, improvement of the network reliability and resilience.
- Possibility of bundling and managing the energy produced by the dispersed generation altogether.
- Optimisation of the energy management because generation and consumption are taken into consideration at the same decision level.
- Possibility of offering ancillary services (like voltage control through the reactive flow control, demand management, etc.).

When the µGrid is based on DC voltage, some additional advantages are presented:

- Bigger simplicity to plug & play new systems to the µGrid and to synchronize the resources each other.
- Great improvement of the connection and the disconnection of the µGrid from the main network since the synchronization process is simplified on the AC/DC converter,
- Facility to maintain a stable voltage since any distributed capacitor can help to reach voltage stability through its storage capabilities. The negative effects of inductances and capacitances under AC become positive in DC (filters and storages).
- Decrement on infrastructure investment because the power flow can be achieved employing only two cables
- Energy efficiency and economical cost enhancement in predominant DC load scenarios.

- Reduction of the harmonics and the reactive power flows emitted by non-linear loads on the MV network. Consequently, power quality is improved and system losses reduced.

6. Annex I: Power Tracking

6.1. Control of the injected active power

The µGrid concept allows a higher integration of distributed generation. In most cases, the impossibility of controlling the active power generated by this kind of resources appears. In order to facilitate as much as possible the sustainable development of renewable energy resources as well as maximizing economic revenues, this renewable energy will have priority whenever possible.

However, many of the systems that convert the primary energy into the electrical energy are based on finding out the 'resonance' between the primary energy and the systems absorbing it. Thereby, a method in charge of searching the Maximum Power Point is required.

6.1.1. Maximum power point tracking (MPPT)

The MPPT system equipped at wind mills is aimed to extract the maximum electrical energy from the kinetic energy accumulated on the wind speed. The operation of most of the wind power plants is based on transforming wind lineal movement into rotational one. Figure 38 shows the relationship between the torque and the angular velocity of the rotor absorbing the mechanical energy:

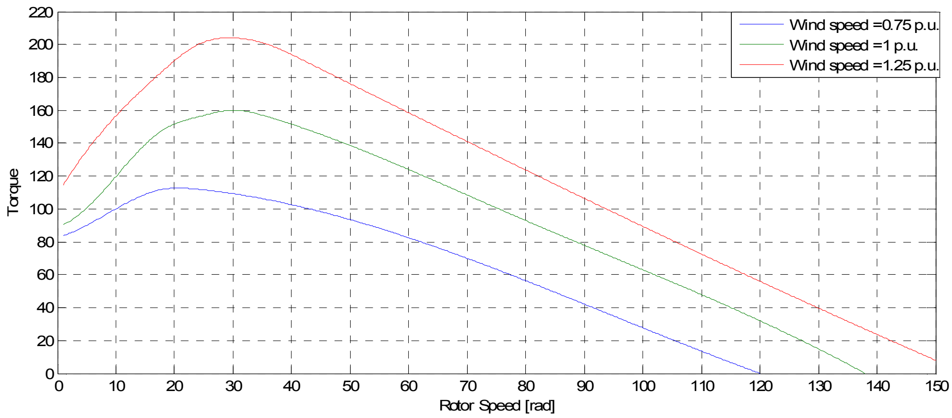


Figure 38: Torque versus rotational speed of a wind turbine for several wind speeds

The power injected to the energetic system without taking into consideration the losses, can be calculated with the following formula:

Equation 14

$$P = T \cdot \omega_{Rotor}$$

This means that, for a given wind speed, there is always a fixed rotor speed that allows the generator to absorb the maximum power.

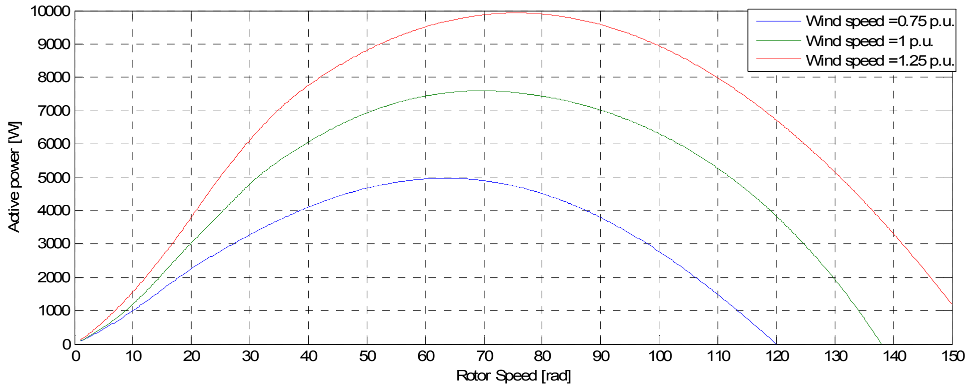


Figure 39: Active power extracted from the wind as a function of the wind lineal speed and the axis rotational speed

Sophisticated controls are used in most wind power generators (up to a few MW) in order to relate the wind speed with the optimal spin of the rotor. However, this procedure requires the measurement of the wind speed at every time and the appropriate adjustment of such relation so as to ensure that the optimum point is reached.

For low power rated wind mill generators, there are other simpler methods of operation around this optimum point which are also employed in PV systems. These procedures are based on the continuous tracking of the maximum power extracted from the generator. The operation point is appropriately modified so as to find the optimum one.

In the particular case of µGrids, available generation will be probably based on low power units where further investments on the control system are unlikely. In the cases when a micro source that produces AC has to be connected to the DC network while the MPPT is guaranteed, it is possible to employ two different approaches: an inverter or a rectifier plus a DC/DC converter.

It is also easy to operate this kind of systems focusing exclusively on the electrical variables as it can be seen on the following flow chart:

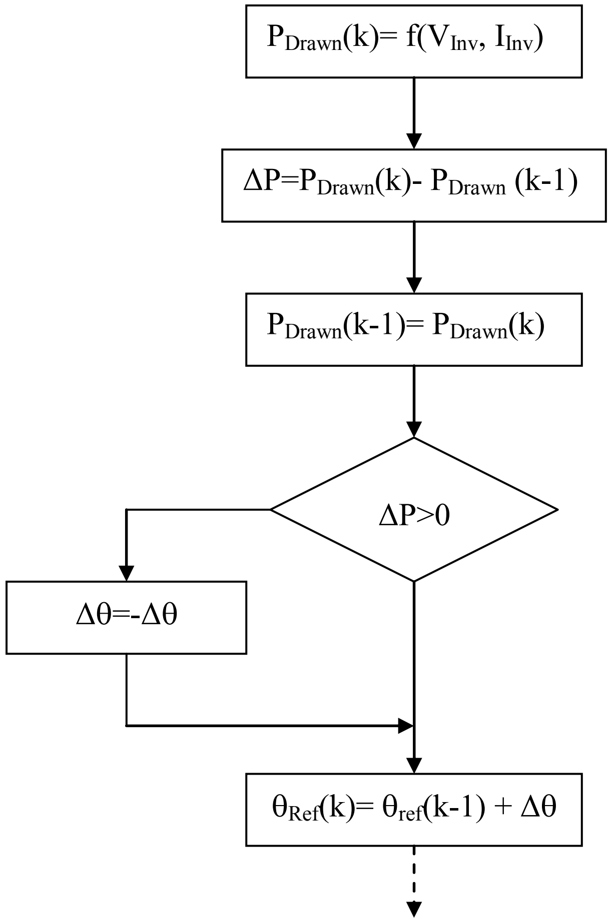


Figure 40: Simple MPPT technique flow chart

The $\Delta\theta$ variable refers to the controlled variable dealing with the power control:

- Phase angle between stator and inverter voltages in the inverter case (see section 6.1.1.1)
- Input voltage in the DC/DC converter case (see section 6.1.1.2).

The time-step depends on the mechanical and electrical characteristics of the device. The active power produced (P_{Drawn}) is measured and its increment or decrement is checked in order to modify the controllable magnitude.

6.1.1.1. MPPT in AC/DC converters

The inverter controls its voltage (V_{Inv}) so as to regulate the active power that flows from the generator to the network. This converter does not introduce harmonics on the rotor of the generator and avoids harmonics torques because the AC voltage is assumed to be perfectly sinusoidal. The inverter is connected to the stator of the generator as shown in Figure 41:

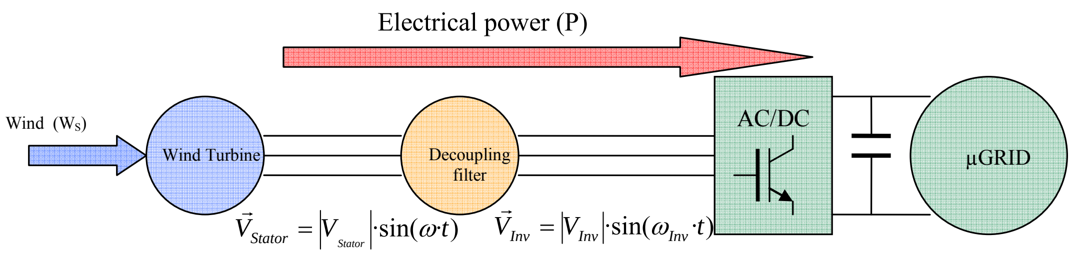


Figure 41: Wind turbine connected to the DC network through an inverter

The inputs and outputs to the wind turbine are the blowing wind speed and the produced electrical power respectively. The stator voltage and its frequency are mainly functions of the previous two variables being related by the curve shown in Figure 39 (with some constants which will depend on the mechanical construction, generator features…). As a function of the operation point in that curve, the rotor speed will be different and consequently, the voltage induced on the stator as well.

Therefore, it is possible to control the active power produced by the wind turbine through the phase angle control of the inverter voltage compared to the stator voltage angle. In the inverter, this angle is modified increasing or decreasing slightly its frequency, displacing consequently the operation point along the curve (Figure 39). A simple control that follows the previously described methodology is shown in Figure 42. In this particular case, reactive power is regulated through the voltage magnitude in order to maintain it as close as possible to zero.

The generated electrical power is controlled through the inverter voltage control adapting its output frequency. It can be noted that the angle between both voltages (θ) determines the active power flowing from one point to the other.

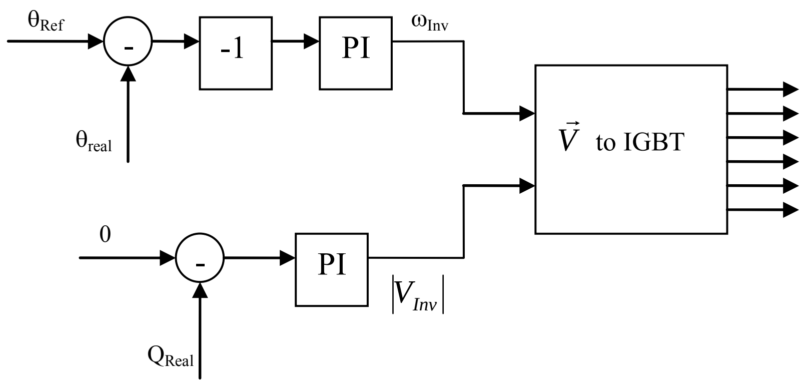


Figure 42: Power flow control

The θ_{Ref} reference is the same as the corresponding one to the flow char of Figure 40.

The inverter voltage can be expressed as follows:

$$V_{INV} = |V_{INV}| \cdot \sin(\omega_{INV} \cdot t)$$

The objective of the following simulations is evaluating the control algorithms of a wind turbine based on the characteristics depicted in Figure 38 and Figure 39. It is assumed that the wind blowing is 1p.u. Both, the stator voltage and the inverter voltage, are decoupled through a 10mH inductance. In the following figures, the way in which the power is extracted and adjusted to track the maximum power point is plotted. They have not been taken into account other secondary effects due to mechanical or electrical issues.

Figure 43 shows what occurs when the wind speed remains constant. In this case, the angle is adjusted so as to maintain the active power at its maximum level:

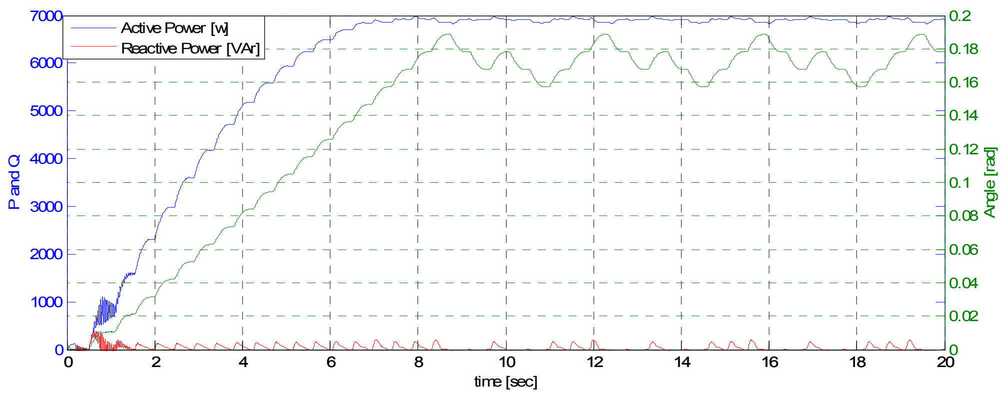


Figure 43: Active and reactive power and controlled angle of the wind generator

It can also be seen how the reactive power is maintained close to zero.

From Figure 43 it can be deduced that the rotational speed of the rotor should oscillate at 70 rad / seg. Results presented in Figure 44, confirm this hypothesis.

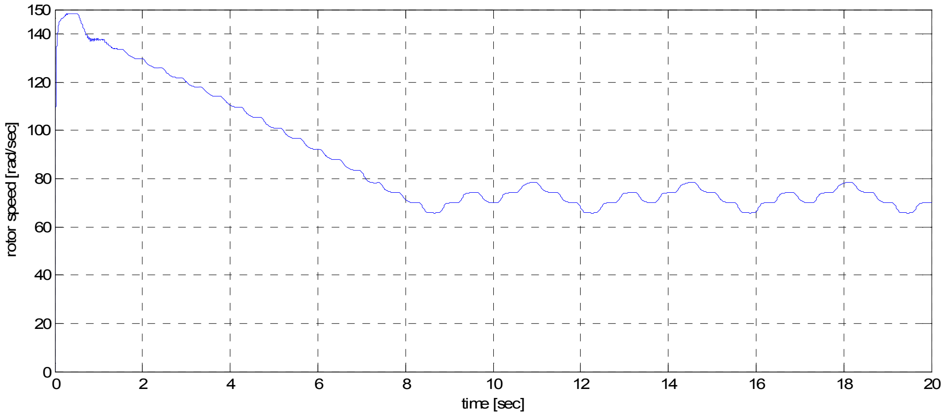


Figure 44: Rotational speed on the wind turbine rotor

The stator voltage depends on the rotational speed and consequently, its magnitude oscillates during the MPPT searching. As the reactive power must take a value as close as possible to zero, a control on the inverter voltage is required. The results of this control, which is very simple (see Figure 42), are presented in the following figure:

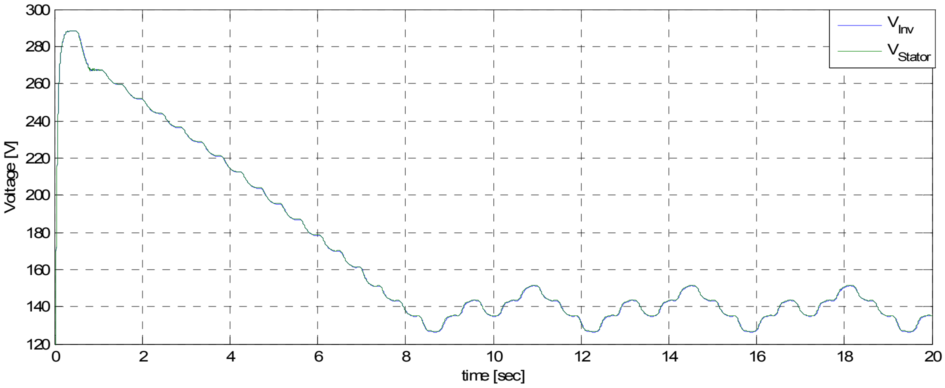


Figure 45: Stator voltage and Inverter voltage

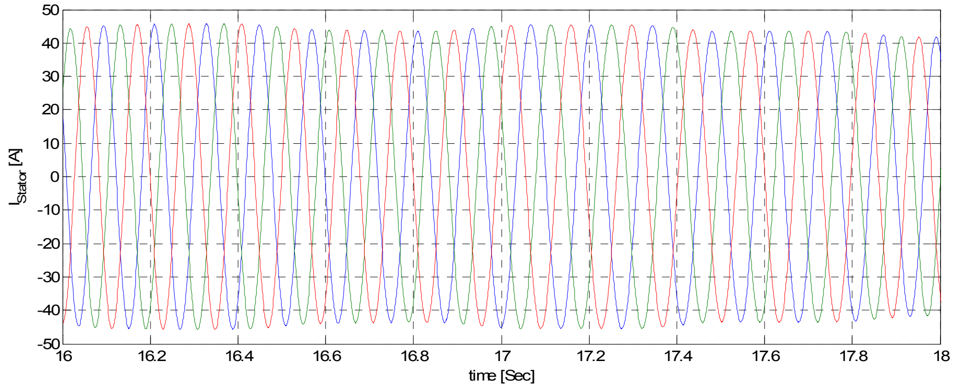


Figure 46: Rotor currents

In a real scenario, the wind speed is variable. In order to evaluate the algorithm under these circumstances, in the following simulation a wind speed that varies from 1.1 and 0.9 p.u. and a frequency of 0.2 Hz. are considered. From Figure 43, it is possible to deduce the boundaries of these simulations.

In Figure 47 a comparison between the wind speed and the active power produced by the wind generator is provided.

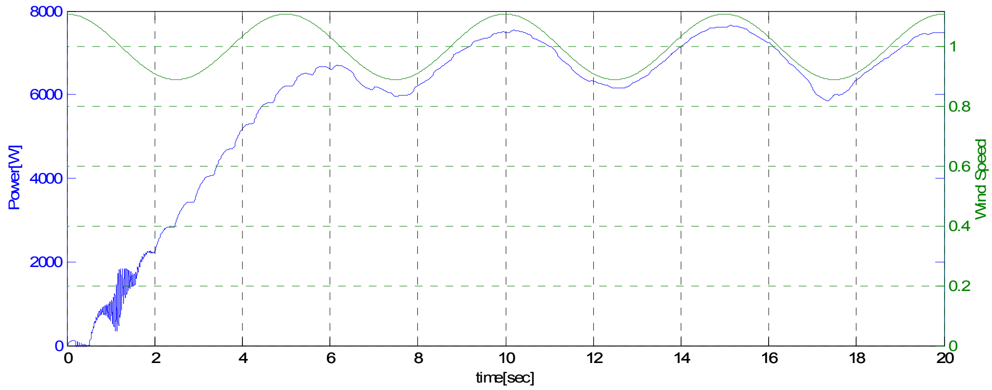


Figure 47: Wind speed and active power extracted from the wind generator

The phase angle between the inverter and the stator voltages that control the active power, as well as the reactive power are plotted in Figure 48:

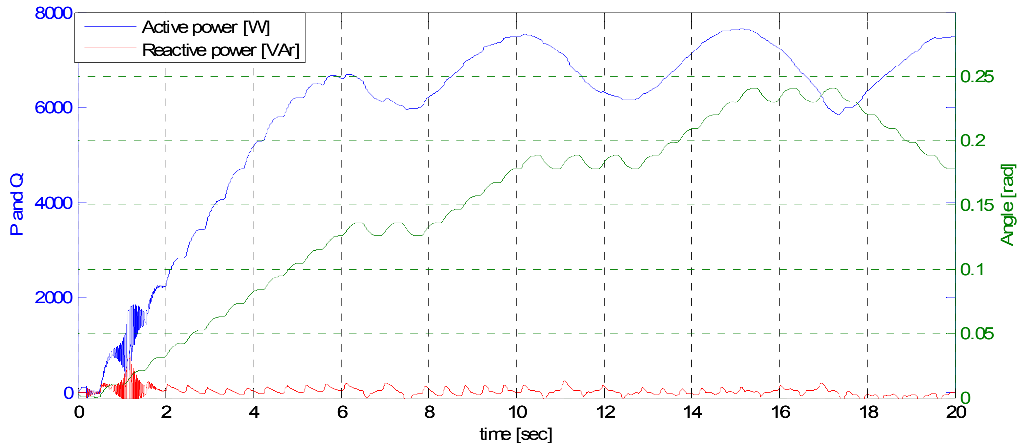


Figure 48: Angle variation to control the active power injection

Figure 49 shows the voltage magnitude corresponding to the generator and the inverter. It can be clearly seen that the voltage magnitude on the generator varies as a function of the rotor speed and that the inverter voltage is re-adjusted so as to decrease the reactive power.

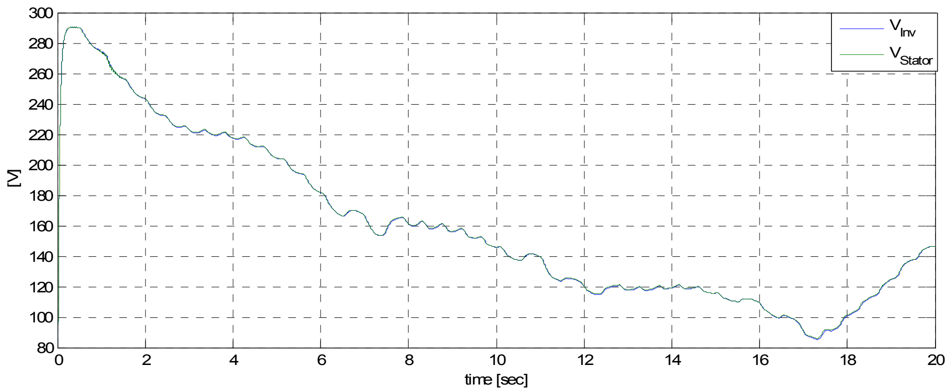


Figure 49: Voltages on the wind generator and inverter

6.1.1.2. MPPT in DC/DC converters

The stator voltage can be directly transformed into DC through the employment of a rectifier (V_{Rect}). The magnitude of this voltage is proportional to the peak value of the stator voltage (V_{Stator}). As such value is a function of the rotor angular speed (ω_{Rotor}), the control of V_{Rect} can modify V_{Stator} whereby ω_{Rotor} is shifted ensuring that the MPPT is reached (Figure 39).

The main advantages of this type of converter are the simplicity on the control and its low cost. These advantages are especially valuable when operating in single phase systems.

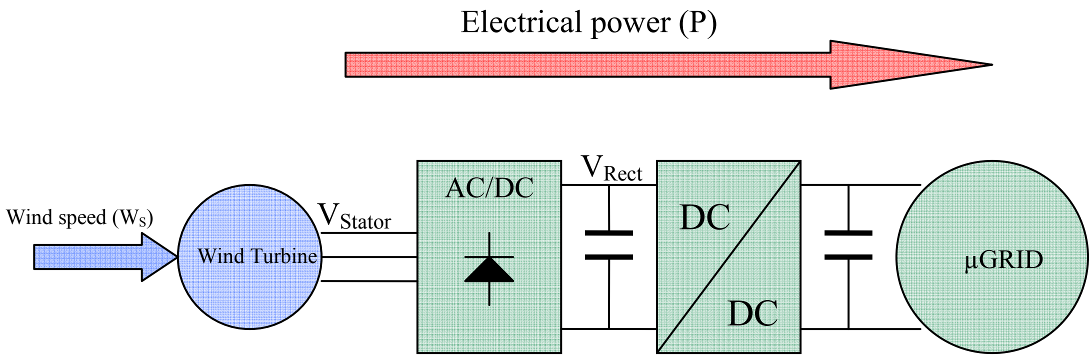


Figure 50: Wind turbine connected to the DC network through a rectifier plus DC/DC converter

The V_{Rect} can be controlled with the DC/DC converter. Now, this variable represents the reference modified by the MPPT so as to search the optimum point.

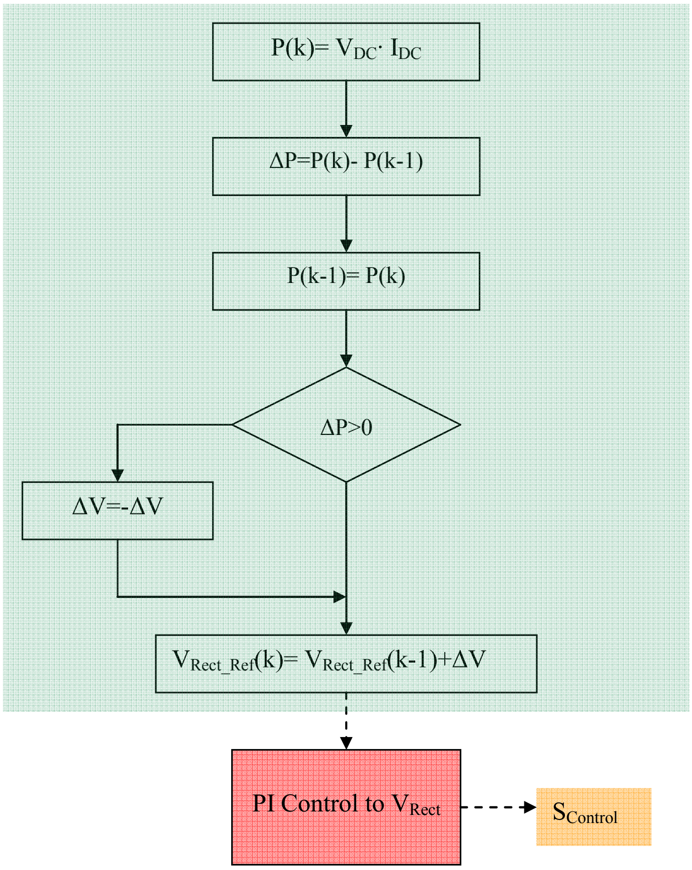


Figure 51: MPPT to control the DC/DC converter

The following figure shows a PI control accomplished on the input voltage of the DC/DC converter, and the corresponding $S_{Control}$ input adjusted in order to obtain the reference voltage scheduled by the MPPT controller:

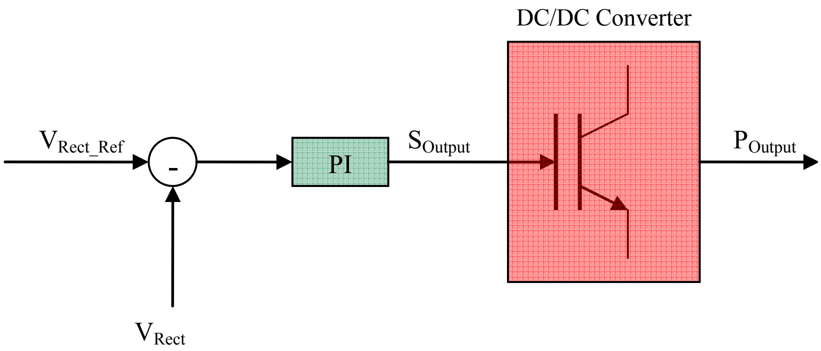


Figure 52: Adjustment of the MPPT reference voltage with the DC/DC converter

A simulation with variable wind speed is conducted under the wind generator connected to the µGrid through a rectifier and a DC/DC converter scenario (Figure 50).

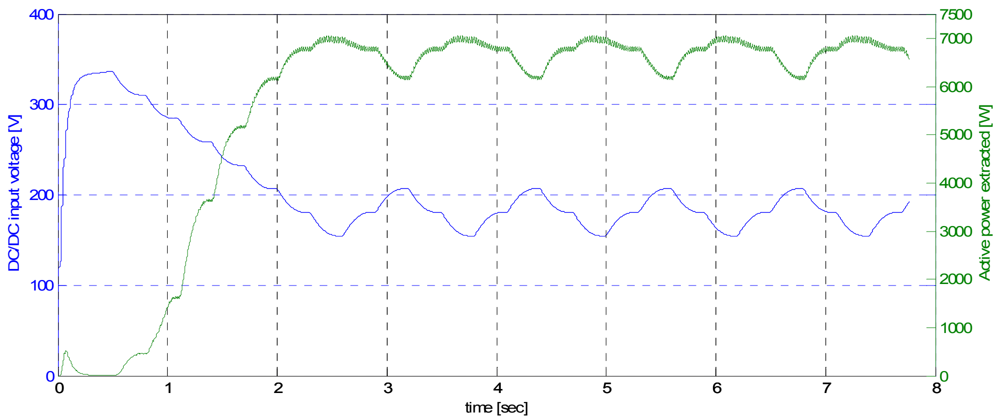


Figure 53: Reference voltage and controlled active power

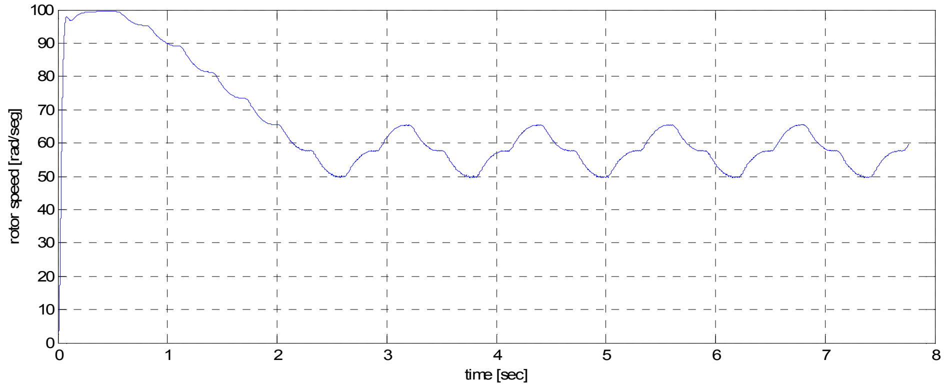


Figure 54: Rotational speed at wind generator rotor

It can be seen how the voltage at the stator oscillates around the stable point.

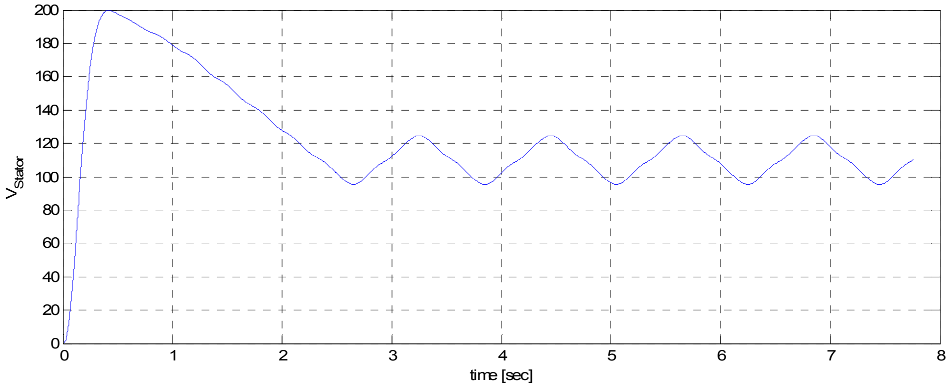


Figure 55: RMS Voltage on the stator side

The main constraint of this converter is the current that feed the rotor. As it is generated by a rectifier, several harmonics appear on the rotor circuit producing vibrations. This current can be compared with the pure sinusoidal reference (see Figure 46).

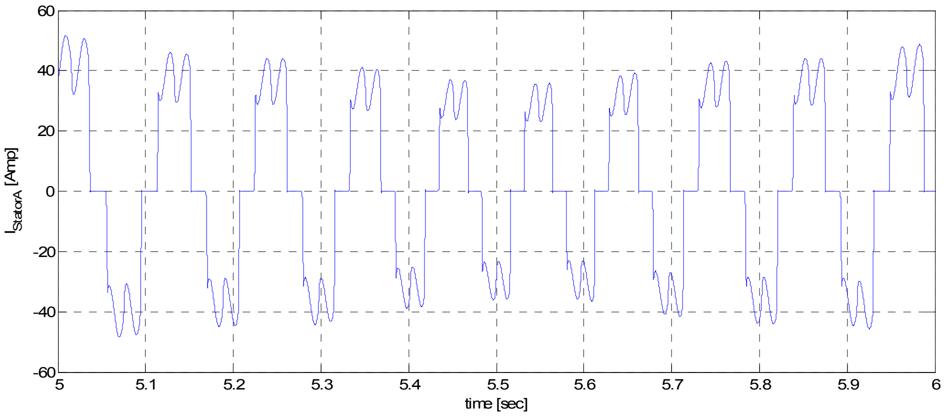


Figure 56: Rotor currents

7. Annex II: Converters

7.1. Converters used in DC based µGrids

There are basically two types of converters that can operate on a DC network:

- AC/DC converters; in charge of transforming the AC available energy into DC.
- DC/DC converters; in charge of readjusting the voltage to the required one by the load and ensuring a suitable voltage regulation.

All devices connected to the DC network, must employ one of the previous converters, independently of the type of device they are: generators, regulation systems, storage devices, loads…

7.1.1. AC/DC converters

There are mainly two technologies for transforming the energy from AC to DC:

- Technologies based on inverters
- Technologies based on rectifiers.

On the inverter case, they use transistor technology, achieving a full decoupling between both sides (AC and DC), a bidirectional control of the power flow and an independent control of the reactive and active power. In this case, it is also possible to reduce the emitted harmonics [7].

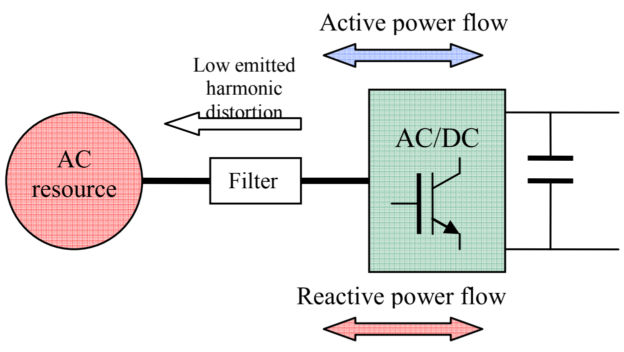


Figure 57: Inverter based AC/DC converter

On the rectifier case, most of them are based on diode or thyristor technology, that is, lined commutated. The power flow on these technologies is unidirectional unless the voltage on the DC side changes its polarity (this implies the µGrid would not be able to export energy to the mains). No reactive control can be accomplished and the emitted harmonics are much higher than in the inverter case. It is noticeable that the cost of this technology is significantly lower than the corresponding one of the inverter technology.

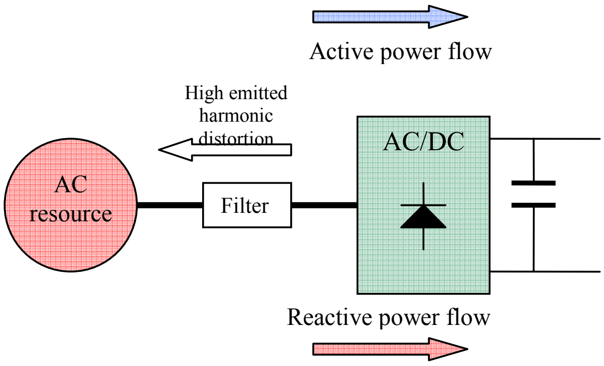


Figure 58: Rectifier based converter

One of the main advantages of the inverter based converters is the possibility of managing active power (absorbing or injecting) even when the voltage on the AC network is affected by a perturbation. This way, the DC network can participate on the AC system regulation delivering its available power, disconnect itself and operate autonomously, or keep on absorbing power. As a consequence, the reliability of the µGrid can be improved.

The mentioned converter (inverter or rectifier based) is in charge of:

- Connecting the main network to the DC network,
- Connecting any AC based generation to the DC network,
- Feeding AC based loads (only through the inverter based converter).

7.1.2. DC/DC Converters

A DC/DC converter can be considered as a system in which the power is transferred from its input to its output, as in a conventional transformer, but taking into account that its voltage value can be completely controlled through an external signal ($S_{Control}$). It is a DC transformer but the turn ratio is controlled by an external signal.

If an appropriate control over $S_{Control}$ is applied, an active power flow control can be achieved. This is an important issue when controlling power instead of voltage such as in MPPT of wind power based sources or in photovoltaic systems.

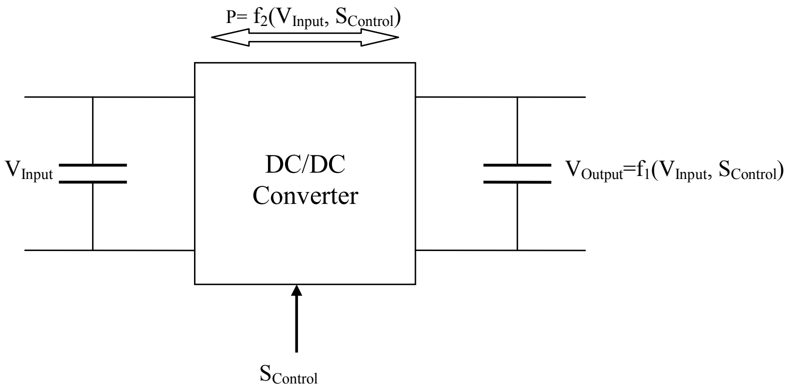


Figure 59: DC/DC converter

The DC/DC converter is the most common device of a DC system. The main functionalities of these devices are the following ones:

- Adapt the voltage from the µGrid DC bus to the devices voltage,
- Control the voltage of the entire µGrid in islanded mode,
- Control of the active power flow output,
- Control the active power flow on the load side,
- Ensure a correct power quality on the voltage (filtering off harmonics and reducing voltage disturbances),
- Operate the MPPT for the resources that require it and control the related power and voltage.

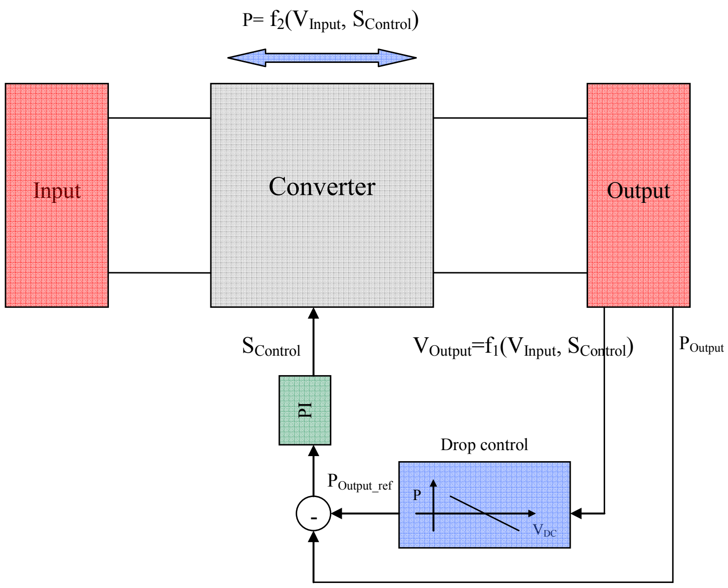


Figure 60: Output power- output voltage control

8. List of acronyms

AC	Alternating Current
DC	Direct Current
DER	Distributed Energy Resources
IGBT	Insulated Gate Bipolar Transistor
LV	Low Voltage
LVPCB	Low Voltage Power Circuit Breakers
MGCC	MicroGrid Central Controller
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
NRG	No Renewable Generation
PCC	Point of Common Coupling
PI	Proportional Integrator
PWM	Pulse Width Modulation
RG	Renewable Generation
RMS	Root Mean Square

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