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Integration of Hybrid Distributed Generation Units in Power Grid

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1. Introduction

The use of renewable energy sources either as distributed generators in public AC networks or as isolated generating units supplying is one of the new trends in power-electronic technology. Renewable energy generators equipped with electronic converters can be attractive for several reasons, such as environmental benefits, economic convenience, social development.

The main environmental benefit obtained by using renewable sources instead of traditional sources, is the reduction in carbon emission. Many countries have adopted policies to promote renewable sources in order to respect the limits on carbon emission imposed by international agreements.

Moreover, renewable energies can be economically convenient in comparison with traditional sources, if the economic incentives for grid connected renewable sources are taken into account or in other particular situations to supply stand alone loads. In some cases, it can be more convenient to supply an isolated load with renewable local source instead of extending the public grid to the load or to supply it with diesel electric generators. In this case, in order to evaluate the economic benefits of renewable energy solution, It is necessary to take in account either the cost of the fuel and the cost of its transport to the load, that can be located in remote and hardly reachable areas.

In addition to the economic benefits, the use of distributed renewable generation units contributes to decentralise the electrical energy production, with a positive impact on the development of remote areas. The exploitation of local renewable sources supports local economies and lightens the energy supply dependency from fuels availability and prices fluctuations.

The integration in the electric grid of distributed power generation systems, located close to the loads, reduces the need to transfer energy over long distances through the electric grid. In this way several benefits are achieved, such as the reduction of bottle-neck points created by overcharged lines, the increase of global efficiency and the limitation of thermal stress on grid conductors. Renewable distributed generation units, if properly controlled and designed can improve the power flow management on the grid and reduce the probability of grid faults, so increasing the power quality of the energy supply.

It's important to evaluate also the possible drawbacks of the increasing number of renewable energy sources on the power-supply stability and quality, both in grid connected

and stand-alone configurations, in order to prevent possible problems with a proper design and management of this generation units.

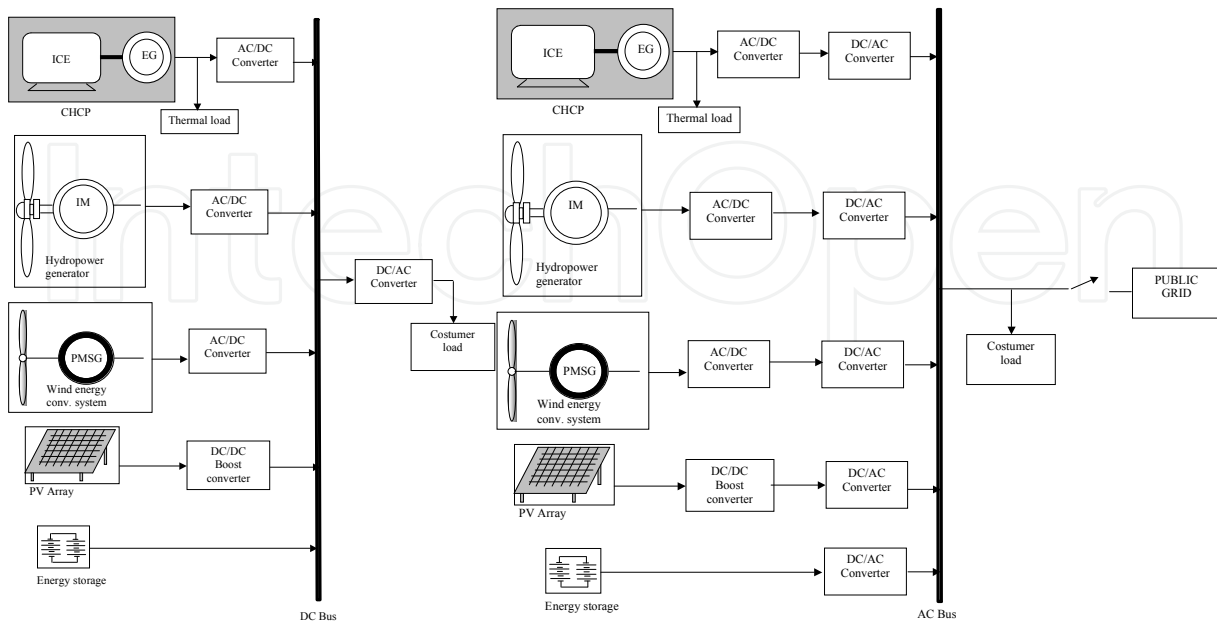


Fig. 1. Example of a HDGU structure with DC and AC bus

The negative influences on power quality of renewable energies derives mainly from two typical characteristics of renewable sources: their randomly varying availability and the presence of a static converter as output interface of the generating plants (with exception for hydroelectric).

The sudden variation of generated power from renewable sources can lead to frequency fluctuation and to grid instability, in grid connected systems, and to total or partial loss of loads power supply in stand-alone systems.

The output interface converter introduces in the electric system voltage and current harmonics that affect negatively the system power quality. On the other hand, if properly designed and controlled, the interface converter can efficiently support the grid in normal operations (reactive power and voltage control) and during grid faults. To reduce this influence, many actions can be taken, typical of the traditional power converters' design technique, such as: low emission topologies, high switching frequency, optimised control techniques and regulators and output passive filters (typically in LC configuration)

To mitigate the effect of renewable sources randomness on power quality different actions are possible: equipping the renewable generation unit with a storage system, integrating to the renewable source a non-renewable source (e.g. a diesel generation unit), integrating in the renewable source a storage system and a non-renewable programmable source.

What is interesting to talk about, as a specific aspect of renewable generation units, is the electric system that lays beyond the interface converter (renewable source, energy storage, power flow control, ecc...) and that allows to transform the random renewable sources into a regulated, flexible and grid-friendly (in grid connected mode) or load-friendly (in stand-alone mode) generation units.

First off all it will be analysed a first solution consists of a renewable source equipped with an energy storage system in stand-alone mode. Secondly a grid connected application of diffused hybrid generation units it will be analysed.

In the following sections some guidelines of the design of renewable generation units will be analysed, focusing on the aspects that influences the power quality of the electrical system. Considering that the renewable sources are mainly wind and photovoltaic, the hybrid generation unit that will be considered, it is composed of a wind turbine, a photovoltaic generator and a battery bank. The hydroelectric source will not be considered, because of its atypical features (no need of static power converter, power availability often regulated by means of natural or artificial basins) that makes it similar to a traditional regulated thermic generation units.

2. Renewable generation units in stand alone mode

When it is necessary to supply electrical loads in stand-alone configuration there is no particular standard that define the power quality requirements. Anyway, the mains concepts of power quality regulation in grid connected systems can be used also for stand-alone systems and as general guidelines, a power quality level close to the one guaranteed for loads fed by the grid can be choose.

On the following sections, a list of the main power quality concepts is presented, focusing on how this concepts, originally dedicated to grid connected systems, can be adapted to stand-alone configurations, in order to obtain some guidelines to improve the performance of these systems.

For general purpose and to simplify the analysis, a stand-alone system, including some loads and one renewable hybrid generation unit equipped with a battery bank is considered.

These considerations can be generalised and adapted to a system of several renewable generation units parallel connected in order to supply the loads in stand-alone configuration. The main considerations regarding the battery bank can be adapted also to other energy storage systems, such as flyback wheels, hydraulic reservoirs, fuel cells, etc.

3. Hybrid renewable generation units in stand-alone mode

3.1 Requirements on voltage waveform (voltage amplitude in normal operating conditions)

In the considered renewable power units, the interface between power generators and loads is made by one ore more static converters. It is important that one of this static converter is a voltage controlled inverter (interface converter) that generates a voltage waveform corresponding to a certain reference given to its control system. By regulating the voltage reference signal, it's possible to obtain a sinusoidal voltage waveform with desired frequency and amplitude, within the limits of the power converter.

In order to maintain the nominal voltage level on the loads, it is important to include in the voltage regulator of the interface converter a compensation term that takes into account the voltage drops on the line impedance, by measuring the current drawn by the loads as it is shown in Fig.2.

Some consideration can be made about the Fig.2:

- The line connecting the power plants and the loads, in small application is a low voltage line, thus characterised by a mainly resistive impedance. The compensation term in the regulator should take into account the line impedance value and typology (reactive or resistive).

- Depending on the interface converter configuration and on the grid number of phases, the actuator that defines the switching command can be chosen according to different techniques: space vector, PWM, hysteresis, ecc...
- The dynamic of the interface converter regulator defines the ability of the converter to maintain a constant voltage on the loads even in case of sudden changes in the load power demand. To prevent the voltage amplitude to move from its nominal value, even in case of sudden changes in the loads, the interface converter regulator should be as fast as possible. On the other hand an excessive speed of the regulator can produce an instability behaviour of the system, for the presence of high frequency harmonic components in the measured voltage and currents, caused both by the loads and by the converter itself. To prevent this instability, that causes the generation of a highly distorted voltage waveform, the interface converter regulator should be slow enough to be immune from high frequency harmonics in the grid, but fast enough to control the voltage variation on the loads. The regulator indicated in the scheme can be different regulator type (P, PID, hysteresis, fuzzy,etc), but its parameters should be set in order to place the cut off frequency of the regulator at least one decade higher that the voltage frequency.

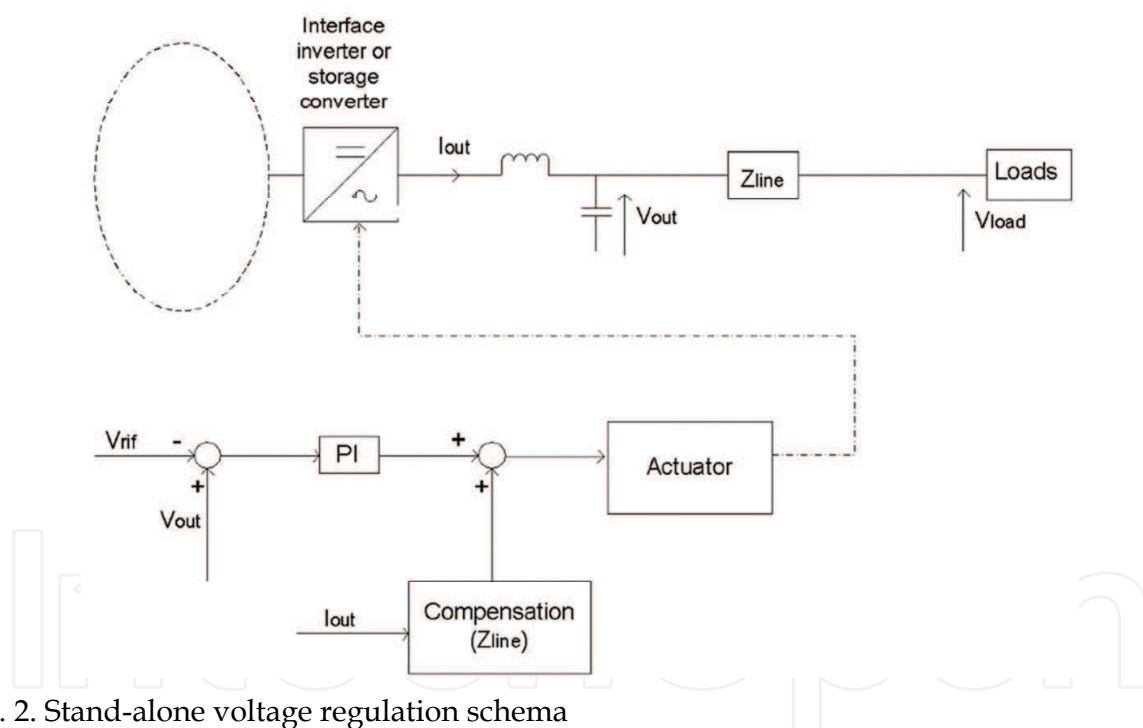


Fig. 2. Stand-alone voltage regulation schema

In case of more than one generation unit connected in parallel in an stand-alone configuration (islanded microgrid) a different control algorithm is needed for the interface converters. Several techniques have been studied to manage the parallel operation of stand-alone inverters and to assure a correct power sharing between the generation units. The more complex control techniques rely on a communication system between generation units. Other techniques can be implemented if no communication system is installed.

The accomplishment, in every node of the islanded microgrid, of the power quality requirements on the voltage value is a problem concerning the coordination between the regulation actions of each interface converter.

3.2 Requirements on voltage frequency

As the system voltage waveform is generated by the interface converter, its frequency can be set by acting on the frequency of the reference voltage (and current) in the voltage regulator (and, if present, in the current regulator).

As for the voltage regulation, in stand-alone microgrids several control techniques can be adopted to maintain the frequency of the supply in the range required for the power quality, with or without communication between paralleled generation units. The only difference from voltage regulation is that the control system of each generation units measure the same electrical frequency in every node of the system. To maintain the nominal frequency of the supply, the control actions of each interface converter must be coordinated through a signal coming from a higher level control system, if a communication system is present, or through a correct setting of the regulation parameters of each converter, if no communication is available.

3.3 Overvoltages and voltage dips

The electrical system of a micro hybrid plants is composed by three elements: the hybrid power plant, the loads, and the low voltage grid converter. Usually the loads are concentrated in a small area, not bigger than a medium rural village, and the hybrid power plant is located as near as possible to the loads, so the low voltage grid has usually a reduced extension and presents a very simple radial structure. If the interface converter and its regulator working correctly, overvoltage on the low voltage grid can only be generated by faults or environmental phenomena (lightening) on the grid. Due to the reduced extension of the grid, these events are very rare and can be reduced by carefully designing and installing the grid components.

The considerations about the overvoltages can be extended also for voltage dips (sags). The main cause of voltage dips on grid connected loads is the fast reclosing action of switches in order to eliminate transient faults. In stand alone systems no fast reclosing procedure is necessary due to the low extension of the grid, so, voltage dips are not a problem to solve in this systems.

3.4 Flickers

Flickers are fast variations of the voltage supplied to the loads. These voltage oscillations are generated by repetitive load connection and disconnection or by their discontinuous current absorption. Usually, the loads that origins flickers are big industrial loads, such as welders and arching furnaces. Stand alone hybrid power systems do not usually fed loads of this kind, anyway, if that may occur, the component who might prevent the flicker is, once again, the interface converter and its regulator.

Depending on its regulator speed and performances, the interface converter can be compensate the fast variations in the current absorbed by the loads and prevent flickers.

3.5 Harmonics

High frequency harmonic components in the electric system can affect the grid current and the grid voltage too. Due to the impedances of the system, current harmonic components can produce voltage harmonics, and vice versa. Anyway, the primary causes of voltage and current harmonics are quite different.

The harmonic components in grid current are produced by the loads equipped with electronic devices that absorb high frequency current components. These harmonic components can be reduced only by acting directly on the loads.

The voltage harmonic components are introduced in the system by the interface converter and are produced mainly by the switching of electronic components. Voltage harmonics can also be presents due to regulator malfunctioning or due to harmonic components at frequency lower than the cut off frequency of the power bus regulator. Generally, the power bus presents a parallel connection of the converters dedicated to the renewable generators, that inject power into the power bus, and of the converter dedicated to the storage system, that exchange power in both directions between the power bus and the storage system. To eliminate the grid voltage harmonics produced by the voltage harmonics on the power bus, it is necessary to guarantee the stability of the voltage level of the power bus. This can be achieved with a proper power flow control algorithm and by adding filters at the output of the other static converters connected to the power bus. Moreover, the dynamic behaviour of the storage system and its converter, can affect the harmonic content of the power bus voltage and, consequently, also of the grid voltage. The storage system converter regulator should maintain the energy balance between loads and sources on the common power bus. Any energy imbalance on the common bus causes fluctuations on the power bus voltage. More fast is the storage converter regulator and the more stable is the voltage on the power bus. A rapid compensation of energy unbalance on the power bus can be achieved imposing to the storage system fast and sharp charging and discharging operations, but these operations can lead to its premature ageing.

If some voltage harmonics still remain on the power bus and are transferred to the grid voltage, a solution to eliminate these can be the reducing of the cut off frequency of the inverter regulator, in order to make it able to compensate this lower harmonic components, too. Anyway, the cut off frequency of the interface inverter regulator should not be less at least one decade of the grid frequency.

3.6 Supply interruptions

In stand alone systems, the main issue regarding electric Power Quality is to guarantee the supply continuity. The main causes of power supply interruption in stand alone systems are due to fault in the renewable power plants. The electric grids that connect the renewable power plant to the loads is usually very short and simple so a fault event on the grid is very rare.

In stand alone systems, the supply interruptions caused by a lack of energy of the renewable power plants can be analysed using the concept of Loss of Power Supply or Loss of Load (LPS or LOL) and Loss of Power Supply Probability or Loss of Load Probability (LPSP or LOLP). The LPS and LPSP concepts are more or less equivalent to the LOL and the LOLP concepts, so only the LPS and LPSP indexes will be considered.

The LPS is the total energy required by the load that is not supplied during an interruption. The LPSP index depends on the duration of the interruptions and on the load power demand during interruptions. If a supply interruption occurs when no power is requested by the loads, it has no effect on the LPSP value.

The LPSP is a global index that defines the hybrid system availability during a particular period of time, usually one year; it takes into account the sum of the LPS and the energy demand during the year. As the renewable sources have a seasonally behaviour, the one year period is a good choice to evaluate the performances of hybrid systems.

The LPSP index expresses the probability to have a supply interruption on the stand alone loads, due to a lack of power of the renewable power plant. In an existing system, the LPSP can be defined as the sum of the energy not supplied to the loads during the supply

interruptions occurred in a year, divided by the total energy required by the loads during the year as indicated in (1)

$$LPSP = \sum_{i=1}^N E_{l_NS,i} / E_{l_tot} \quad (1)$$

where N is the number of supply interruptions during one year, $E_{l_NS,i}$ is the total energy required by the load and not supplied during the interruption I and E_{l_tot} is the total energy required by the loads during the year. The LPSP can also be expressed in function of the power demand of the loads during the supply interruption and the duration of the supply interruptions as indicated in (2)

$$LPSP = \left(\sum_{i=1}^N \int_{\Delta_{SI,i}} P_{l_NS,i}(t) \cdot dt \right) / E_{l_tot} \quad (2)$$

where $P_{l_NS,i}$ is the load power demand during the supply interruption I and $\Delta_{SI,i}$ is the duration of each supply interruption.

The expression (2) of the LPSP is more precise and it allows to take into account also the partial losses of supply. The partial losses of supply are produced by the intentional separation of the loads in case of lack of energy from the renewable power plants, or due to others critical conditions such as a low state of charge of the energy storage system. The separation of a part of the total loads is possible if, during the designing of the stand alone system, loads have been separated at least in two groups: privileged loads (PL) and non privileged loads (NPL). NPL loads are connected to the renewable generation unit through a controlled switch.

The separation of NPL is used to prevent the excessive discharging of the storage system and to extend as far as possible the supply of the PL. During partial LPS, the power not supplied to the loads is equal to the power demand of the non privileged loads. The LPSP can be expressed as indicated in (3).

$$LPSP = \frac{\overbrace{\sum_{i=1}^{N_T} \int_{\Delta_{SI,i}} P_{l_NS,i}(t) \cdot dt}^{\text{globalLPS}} + \overbrace{\sum_{j=1}^{N_P} \int_{\Delta_{PSL,j}} P_{NPL_NS,j}(t) \cdot dt}^{\text{partialLPS}}}{E_{l_tot}} \quad (3)$$

This separation between global LPSs, that affects all the loads, and partial LPSs, that affects only the NPL, is useful if an economical evaluation of the LPSP must be carried out, e.g. to perform a techno-economical optimum sizing of the renewable power plant.

A specific value of LPSP can be one of the requirements to be achieved through a proper design of the stand alone system, as a quality requirement of the supply service to the loads. The design value of LPSP can be calculated from the curve of the load demand during the year, the weather data (wind speed, solar radiation, temperature) in the system location, the size of the storage system and of the renewable generators of the hybrid power plant and the power management control strategies implemented in the renewable power plant.

From the size of the renewable generators and the weather data of the location it is possible to calculate the power available from the renewable energies, $P_{gen}(t)$. The power demand curve of the two groups of loads ($P_{PL}(t)$ and $P_{NPL}(t)$) during the year can be known from enquiry on the territory or, more often, must be assumed by the designer knowing the type

and number of loads that will be connected to the system. To define the working operations of the battery bank, its rated capacity, C_{nbat} , and its minimum admitted State Of Charge, SOC_m , should be defined. The value of SOC_m is usually indicated by the battery manufacturers, as the minimum rate of discharge of each discharging cycle that guarantees the required lifetime of the battery bank. In normal operation the battery maintains the energy balance between the sources and the loads, until its discharging rate doesn't exceed the minimum thresholds. When SOC_m is reached, the loads are disconnected and the renewable energy is used only to charge the storage system.

To evaluate the design LPSP, it is possible to divide the reference period T (one year) in time steps Δt usually equivalent to one hour: If the energy demand from the loads is higher than the sum of the energy available from the sources and the energy still cumulated in the storage system, there is a loss of supply and the LPS(t) can be calculated as indicate in (4).

$$\left. \begin{array}{l} \text{if } \overbrace{(P_{PL}(t)+P_{NPL}(t)) \cdot \Delta t}^{\text{Energy_demand_from_loads}} > \overbrace{P_{gen}(t) \cdot \Delta t}^{\text{Energy_from_sources}} + \overbrace{(SOC(t)-SOC_m) \cdot C_{nbat} / 100}^{\text{Energy_available_in_storage}} \\ \Rightarrow LPS(t) = (P_{PL}(t)+P_{NPL}(t)) \cdot \Delta t - P_{gen}(t) \cdot \Delta t - (SOC(t)-SOC_m) \cdot C_{nbat} / 100 \\ \text{if } (P_{PL}(t)+P_{NPL}(t)) \cdot \Delta t \leq P_{gen}(t) \cdot \Delta t + (SOC(t)-SOC_m) \cdot C_{nbat} / 100 \Rightarrow LPS(t) = 0 \end{array} \right\} \text{for } 100\% > SOC(t) > SOC_m \quad (4)$$

When the battery SOC (t) reaches the threshold SOC_m the loads are disconnected, the battery is charged with the energy coming from the renewable sources and the loads are not supplied. The global supply interruption goes on until the battery is recharged at a certain level of charge, SOC_{reload} situated between the fully charge condition and the minimum threshold, SOC_m .

$$LPS(t) = (P_{PL}(t) + P_{NPL}(t)) \cdot \Delta t \quad \text{for } SOC_m < SOC(t) < SOC_{reload} \quad (5)$$

More refined and complex strategies can be adopted to reduce as far as possible the LPSP on privileged loads, e.g. it is possible to disconnect the NPL when the battery SOC(t) exceed an imposed threshold, SOC_{NPL} , higher than SOC_m . In such way, the remaining energy stored in the battery is used to supply only the PL if the renewable energy is not enough and the design equations (4) became the following.

$$\left. \begin{array}{l} \text{if } (P_{PL}(t)+P_{NPL}(t)) \cdot \Delta t > P_{gen}(t) \cdot \Delta t + (SOC(t)-SOC_{NPL}) \cdot C_{nbat} / 100 \\ \Rightarrow LPS(t) = (P_{PL}(t)+P_{NPL}(t)) \cdot \Delta t - P_{gen}(t) \cdot \Delta t - (SOC(t)-SOC_{NPL}) \cdot C_{nbat} / 100 \\ \text{if } (P_{PL}(t)+P_{NPL}(t)) \cdot \Delta t \leq P_{gen}(t) \cdot \Delta t + (SOC(t)-SOC_{NPL}) \cdot C_{nbat} / 100 \Rightarrow LPS(t) = 0 \end{array} \right\} \text{for } 100\% > SOC(t) > SOC_{NPL}$$

$$\left. \begin{array}{l} \text{if } P_{PL}(t) \cdot \Delta t > P_{gen}(t) \cdot \Delta t + (SOC(t)-SOC_m) \cdot C_{nbat} / 100 \\ \Rightarrow LPS(t) = P_{NPL}(t) \cdot \Delta t + P_{PL}(t) \cdot \Delta t - P_{gen}(t) \cdot \Delta t - (SOC(t)-SOC_m) \cdot C_{nbat} / 100 \\ \text{if } P_{PL}(t) \cdot \Delta t \leq P_{gen}(t) \cdot \Delta t + (SOC(t)-SOC_m) \cdot C_{nbat} / 100 \Rightarrow LPS(t) = P_{NPL}(t) \end{array} \right\} \text{for } SOC_{NPL} > SOC(t) > SOC_m$$

$$LPS(t) = (P_{PL}(t) + P_{NPL}(t)) \cdot \Delta t, \quad \text{for } SOC_m < SOC(t) < SOC_{reload} \quad (6)$$

Analysing the (6), it can be seen that the LPSP, in stand alone systems supplied by a generically hybrid renewable power plants with a storage systems, depends mainly on two design aspects: sizing of the renewable generators and of the storage system and to the control strategies adopted for the energy management.

A compromise between the power quality of the electrical supply and the costs of the system should be reached in the designing of renewable power plants in particular the use of a fuel generation unit to supply the load in case of a lack of energy from the renewable energy sources and the storage system can decrease the LPSP of the system up to zero.

4. Design aspects of HGDU in stand alone mode

As highlighted previously, the Power Quality in stand alone system supplied by a renewable hybrid generation unit depends mainly on the design of the generation units. Three main aspects of the design of renewable hybrid power plants for stand alone operation will be analysed, trying to point which are the possible choices that leads to a higher power quality of supply.

4.1 Sizing

The sizing of renewable generation units is the aspect that mostly affects the continuity of supply in stand alone systems. As it has been highlighted previously, the LPSP of a stand alone system depends on the energy available from the renewable generators and on the energy stored in the battery bank. This two variables are closely related to the sizing both of the renewable generators and of the storage systems, and depends on the control strategy used to manage the power flux in the renewable power plant also.

The optimal sizing of renewable hybrid power plants is a quite complex problem, because it concerns the optimisations of several variables.

In this section, some considerations about the optimum sizing methods are presented, in order to underline the main constraints affecting the sizing of the hybrid power plant and to highlight the drawbacks of a sizing choice in the continuity of the loads supply.

To design a hybrid renewable power plant equipped with storage system, the typology and the size of the renewable generators and of the storage system should be fixed.

4.1.1 Renewable generators and storage system

The choice of the renewable generators type (photovoltaic, wind turbine, hydroelectric, geothermal,...) depends on the renewable sources availability in the location where the system will be installed. The most widespread and easily exploitable renewable source is solar radiation, followed by the wind. Many studies shows that wind and solar radiation distributions have often a complementary behaviour, thus making convenient in many cases to combine wind and solar renewable generators in the hybrid power plants. In the following, this two main renewable sources will be considered, but the analysis can be easily extended also to other renewable generators.

The choice of the storage system should take into account, first of all, that storage systems can be classified into two groups: energy storage systems (batteries, hybrid compressed air systems,...) and power storage systems (super capacitors, flywheels,...). In stand alone systems the first need is to store exceeding energy produced by the renewable sources in order to deliver it to the loads when necessary. For this reason, the more suitable storage

system for stand alone renewable energy power plants are batteries. In some cases high power storage systems (usually super capacitors) can be added in parallel to batteries, in order to reduce the electrical stress when high power peak are requested by the loads.

4.1.2 Sizing variables of the renewable generators and of the storage system

In the case of a hybrid wind/PV power plant, when the renewable generators are working in their maximum power points, the expressions of the power available from the two renewable source are:

power points, the expressions of the power available from the two renewable source are:

$$P_W(t) = \eta_W \cdot \frac{1}{2} \cdot \rho_a \cdot c_p \cdot v_w^3(t) \cdot A_w \quad \text{for the wind turbine}$$

$$P_{PV}(t) = \eta_{PV} \cdot J_t(t) \cdot A_{PV} \quad \text{for the photovoltaic generator}$$

where:

η_W and η_{PV} are the total efficiencies of the renewable generators,

ρ_a is the air density, [kg/m³]

c_p is the power coefficient of the wind turbine, depending on its shape and typology,

$v_w(t)$ is the instantaneous wind speed at hub height, [m/s]

$J_t(t)$ is the instantaneous solar radiation on the tilted surface of the solar panels, [W/m²]

A_w is the area swept by the wind turbine and A_{PV} is the total area covered by the PV panels, [m²]

A_w is the area swept by the wind turbine and A_{PV} is the total area covered by the PV panels, [m²]

The two design parameters on which depends the power available from the renewable generators are the two areas A_w and A_{PV} .

Some more detailed calculations can be done for the wind generator, considering that the power extracted from the wind turbine is typical limited by three speed thresholds, defining the control strategy of the wind generator controller. When the wind speed is lower than the cut-in threshold (v_{cut-in}) the wind turbine is blocked and no power is extract from the wind generator. When the wind speed is between the cut in threshold and the regulation threshold (v_{reg}) the wind generator is kept in the working point corresponding to the maximum power. When the wind speed is between the regulation threshold and the cut-off threshold ($v_{cut-off}$), the wind generator is regulated to supply a constant power, equal to its maximum rated power.

Taking into account the wind speed thresholds, the power available from the wind generator is:

$$P_W(t) = \begin{cases} 0 & \text{for } v_w(t) < v_{cut-in} \\ \eta_W \cdot \frac{1}{2} \cdot \rho_a \cdot c_p \cdot v_w^3(t) \cdot A_w & \text{for } v_{cut-in} < v_w(t) < v_{reg} \\ P_{n,max} & \text{for } v_{reg} < v_w(t) < v_{cut-off} \\ 0 & \text{for } v_w(t) > v_{cut-off} \end{cases} \quad (7)$$

The maximum energy stored in the battery bank is the product of the battery nominal voltage (V_{nbat}) and rated capacity (C_{nbat}):

$$E_{nbat} = C_{nbat} \cdot V_{nbat} \text{ [Wh]} \quad (8)$$

To guarantee a certain expected lifetime of the battery, expressed in number of charging and discharging cycles, the batteries suppliers indicated a minimum state of charging that it not possible to exceed in the battery lifetime. The minimum state of charge admitted (SOC_m) depends on the desired expected lifetime of the battery, expressed in number of cycles. The battery lifetime is affected by many operating conditions, such as the ambient temperature, the amplitude of high frequency ripple in the battery voltage and current, the possibility to charge the battery following the optimum V-I curves, etc.

The available capacity of the battery bank C_{avbat} is lower than its nominal capacity and depends on the value of SOC_m :

$$C_{avbat} = C_{nbat} \cdot (100 - SOC_m) / 100 \quad (9)$$

In the same way, the available energy in the storage system, E_{avbat} , is defined as :

$$E_{avbat} = C_{avbat} \cdot V_{nbat} = E_{nbat} \cdot (100 - SOC_m) / 100 \quad (10)$$

The battery bank voltage depends on the battery converter configuration and on the voltage levels in the renewable power plant.

The number of desired charging/discharging cycles in the battery lifetime depends on economical evaluations that take into account the cost of battery replacements and the expected lifetime of the entire stand alone system. To guarantee the desired number of charging/discharging cycles at specific operating conditions of the battery it is necessary to define a correct value of SOC_m . The main design variable that should be defined by the designer of the renewable power plant is the desired available capacity of the battery, which defines the total energy that can be managed (stored or supplied) by the storage system without exceed the minimum state of charge SOC_m .

4.1.3 Sizing constrains

The two main constraints affecting the sizing of the renewable generators and of the storage system are the overall cost of the system and the continuity of supply to the loads.

The overall cost of the system is composed by two contributions: the initial capital investment and the maintenance cost. The initial cost is strictly related to the size of the renewable generators and of the battery bank. The main contribution to the maintenance cost is due to the battery replacements during the lifetime of the system, that is usually much longer than the battery lifetime. Globally, the battery cost has a great impact on the total cost of the system, because it affects both the initial investment and the maintenance cost.

The LPSP is a constraint in the design of renewable power plants that have a big influence on the overall cost. As it can be seen from the LPSP expression (), the availability of loads energy supply increases if both the renewable generators and the battery bank sizes are increased. In some cases, depending on the load power demand and the sources power availability, the LPSP can be increased only using bigger renewable generators. To reach higher values of LSPS especially in case of a low overlap between the source availability and

the load profile, it is necessary to increase the battery capacity also in order to improve the supply continuity.

However, the renewable generators size increasing can allow to reach the desired level of LPSP with a less economical effort. A drawback of this design choice is the possibility to have some wasted energy in the system life cycle. The wasted energy is the amount of energy that could be converted from the renewable generators but can't be used to supply the loads nor to charge the batteries, because they are already completely charged. A waste of energy appears when the load demand and the energy availability from the sources are not overlapped and the storage system capacity is too small to treat the whole energy available from the sources and not directly supplied to the load. The wasted energy doesn't imply a waste of money, thus it can be a designer choice to oversize the renewable generators (or to undersize the battery bank) in order to achieve an acceptable LPSP with lower costs than if the same LPSP is achieved avoiding any waste of energy in system.

The size of the renewable generators and of the storage system is the result of a compromise between the total cost of the system and the continuity of supply to the loads, often reached through an iterative procedure.

Usually, no fixed value is set for the LPSP during the designing of the system. The LPSP target value is usually fixed by the designer taking into account the loads typology and profile and the renewable sources availability. In some cases the supply of some loads should be guaranteed in case of complete lack of the renewable sources for a certain period of time. In the telecommunication application, for example, the supply of each telecommunication station is usually guaranteed for three days with no contribution of the renewable sources. When this performances are required, the size of the minimum storage system is directly dependent on the load power and on the time period where the supply must be guaranteed. If it necessary to guarantee some days of supply only by batteries it is possible to have a very expensive storage systems, but also have a very high quality of supply. Considering that the stand-alone loads present a condition of very high quality supply, comparable to the one guaranteed from UPS in grid connected systems, the costs of renewable systems able to guarantee for a certain period the power supply with no renewable sources, are completely justified.

4.2 Plant configurations

In all hybrid power plants configurations of there is a **power bus**, that is the section of the circuit where all the sources, the interface inverter and the energy storage systems are connected in parallel. Maintaining the energy balance on the power bus of the hybrid power plants is the main condition to maintain the stability of the system.

There are many different power plant configurations, that can differ by the nature of the renewable sources, by the type of the hybrid storage system and by the kind of converters used. These hybrid power plants configuration are usually classified in function of the nature of the power bus (AC bus at frequency line, DC bus or high frequency AC bus).

The main choice to be made regarding the hybrid plant topology concerns, first of all, the type common power sharing bus (DC or AC bus) and, secondly, the typology of the static converters dedicated to the sources and to the battery bank

4.2.1 Common power bus

The two typical AC bus and DC bus configurations of a wind/PV hybrid power plant equipped with a battery bank are reported in figure 3 and 4.

To select the bus configuration of the hybrid power plant several aspects should be taken into account:

Type of loads and sources. If the loads operate at DC (computer servers, DC lamps, DC motors,...), the sources are only PV arrays and the storage system is made by electrochemical batteries, which produce power at DC, then the obvious choice is to use a DC bus, in order to avoid an interface DC/AC converter to feed the loads and to reduce the complexity of the sources and the battery converters.

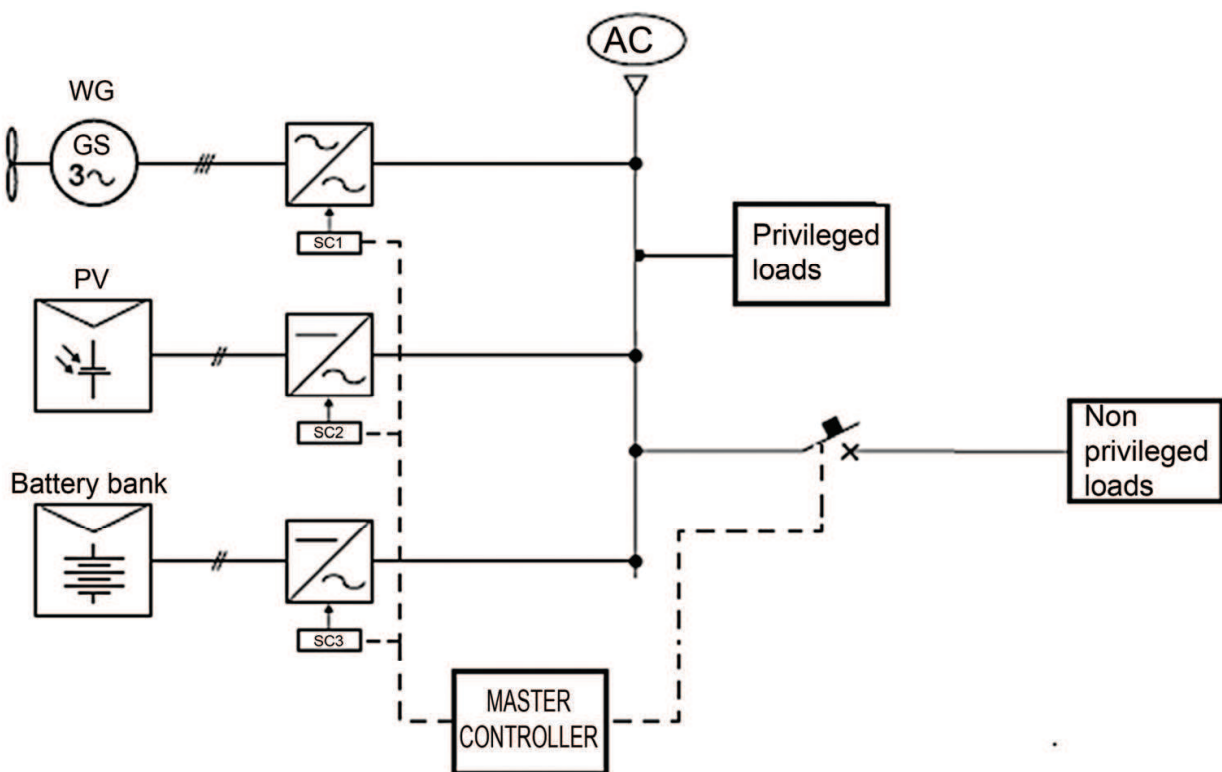


Fig. 3. AC bus configuration of hybrid wind/PV generation unit with battery bank, in islanded mode

If the loads are industrial machines operating at line frequency, the sources are AC generators (doubly fed or synchronous generators) and the storage system is made by electrochemical batteries, then an AC line may be a better system since the loads can be directly connected, thus eliminating the DC/AC interface converter.

No sources and very few loads require high frequency (mainly fluorescent lighting and compressors). For this reason the high frequency AC bus won't be analysed in the following, even if it leads to reduce the size of the passive components, in comparison with grid frequency AC bus.

Control system. Converters on a DC bus system can be simpler than those on a line-frequency AC bus system, and the control for the DC bus is simplified since frequency control is not necessary. In DC bus configurations only active power flow has to be regulated and it is controlled simply acting on the DC voltage level of the common DC bus. Moreover, the flow direction is closely related to current direction. Hence, active power control can be based only on current flow. In AC bus systems active and reactive power flow should be controlled, monitoring both the amplitude and the frequency of the AC bus

voltage. Secondly, the phase shifting between voltage and currents should be monitored in order to control the power flow direction.

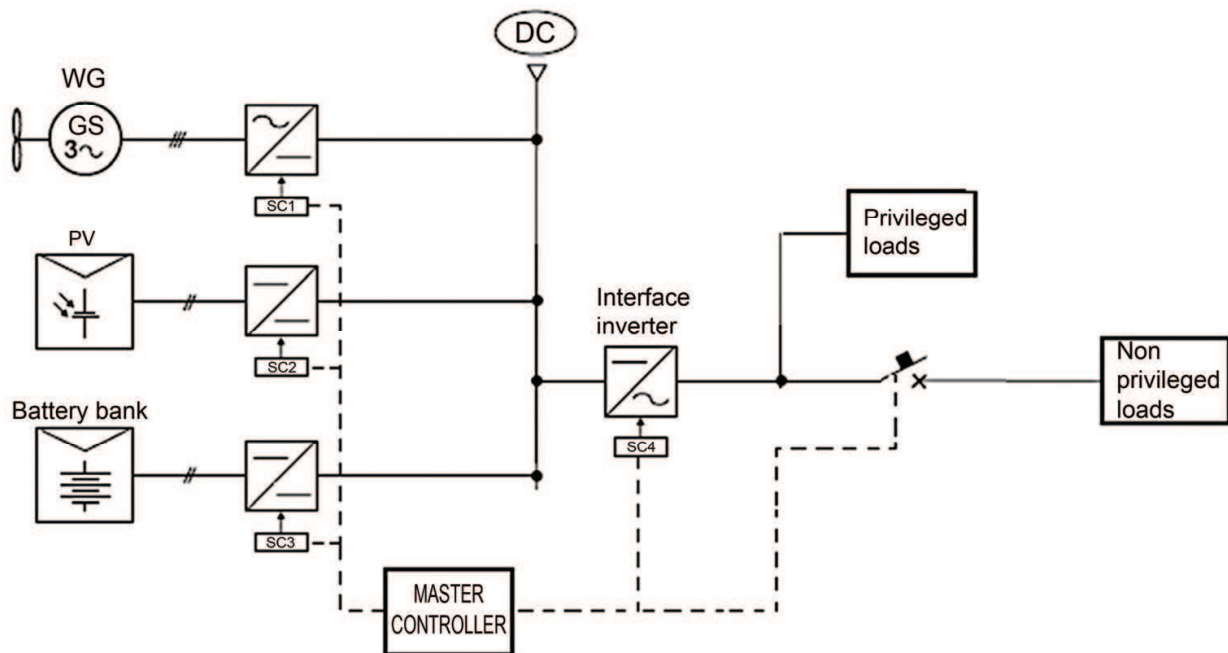


Fig. 4. DC bus configuration of hybrid wind/PV generation unit with battery bank, in islanded mode

Modularity. In low voltage AC bus hybrid systems, AC bus voltage amplitude and frequency are the same of standard low voltage AC public grid, in order to directly connect the AC loads to the AC bus. Any existing power source unit (PV module + DC/AC converters or wind turbine + doubly fed asynchronous generator, etc.) designed to be connected to the AC grid can be added in parallel on the AC bus of a hybrid system. In this way, the generating units can be acquired from different suppliers and additional generating units can be added if the load demand grows without big complications, paying only attention to not exceed the maximum power capability of wirings, and of the common structures of the hybrid systems.

In DC bus hybrid systems, the DC bus voltage level has not a standard value, as for AC bus systems, because it depends on the voltage level of the sources and of the configuration chosen for the source converters.

For example, In order to avoid the output transformer to adapt the voltage level of the DC/AC interface converter to the AC voltage (220 V) needed to feed standard loads, the DC bus voltage should be fixed around 400 V. In this case it may be necessary to add a DC/DC conversion stage between the renewable generation units (and the battery bank) and the DC bus, to adapt the output voltage level of the sources (and of the battery bank) to the required DC bus voltage level.

Another design choice could be to insert a transformer between the DC/AC interface converter and the loads, and to adapt the DC bus voltage level to the more convenient value for the renewable generation units.

Because the DC bus voltage does not present a standard voltage value only dedicated generation units can be connected in parallel to the DC bus. This condition limits the

possibility to change suppliers of the system components and to connect additional generation units if required.

Efficiency. The global efficiency of the system depends on many aspects: renewable sources peak power related to the loads rated power, number and typology of converters, and power flow management. It's difficult to state which one of the two configurations is the more efficient in a general sense. Without taking into account a specific project, only some preliminary consideration can be made.

One of the main causes of power losses is the storage battery bank, due to the self-discharge rate and its charging and discharging efficiencies. So, the overall efficiency of an hybrid system is affected by the rate of active energy that has to be stored in the battery bank before being delivered to the loads. Moreover, the power flow management algorithm and the renewable source peak power related to the loads rated power have a great influence on the overall efficiency of an hybrid generation system.

In AC bus configurations transformers can be used to adapt generating units and storage system voltage level to the standard AC low voltage required to the load. In DC systems, additional conversion stages could be required to raise the output voltage of generation units and the storage system, or the system can be managed at low DC voltage, with no additional conversion stage but with an output transformer between the DC/AC interface converters and the loads. Both transformers efficiency and conversion stages efficiency depends on the voltage level of the system (higher voltages mean lower currents and consequently lower losses on conductors and lower switching losses) and they change according to the working condition of the system: usually transformers have the higher efficiency at rated power, while converters have a higher efficiency at low power levels.

Even if AC bus configuration has one converter less this does not implies a higher efficiency. It is necessary to analyse the structure of the converters to understand how many conversion stages are necessary to reach the loads voltage levels. In addition, it is necessary to consider that in the DC bus configuration, the DC/DC battery converter can be eliminated, if the voltage level of the battery bank is adequate to the DC bus voltage. This solution can increment the system efficiency, but can lead to a faster ageing of the batteries.

Reliability. In AC bus systems the critical component is the battery converter. Usually the battery converter is a VSI and it provides the voltage reference on the AC bus. The battery converter act as the grid in grid connected systems: it set the frequency and the amplitude of the AC bus voltage and it maintains the power balance between loads and sources. The power source converters are current controlled inverter, in order to inject on the AC bus the current corresponding to the maximum power available from the sources or to a reduced power level indicated by the power flow control system. If there is a fault on battery converter, the system collapses because there is no longer a voltage reference on the AC bus. Even if there is energy available from the sources, without the battery converter the load are not supplied. If there is a fault on one of the source converters the system can continue to supply the load with the energy coming from the other sources.

In DC bus systems there are two critical components: the interface converter and the battery converter. Clearly, if the interface converters breaks the loads can no longer be supplied. The battery converter maintains the power balance between the loads and the sources by regulating the DC bus voltage level around its rated value. If the battery converter shutdown the system can still work but only if the power available from the sources is higher than the power required form the loads and it is necessary to adopt a different power flow control strategy.

Overall costs. The overall cost of the system (Lyfe Cycle Cost) can be divided in two parts: initial investment costs and life operation costs. The initial investment depends mainly on the renewable generators peak power and on the battery bank nominal capacity. Also the converters number and design can affect the initial investment costs. Solution with less converters, such as the AC configuration or the DC configuration without battery converter, have smaller initial costs. The use of simpler converters topology with a small number of controlled switching components (usually IGBT) can reduce the initial cost of the system too.

The life operation cost is mainly affected by the number of replacement of the battery bank during the system life. The average life of PV panels is supposed to be at least of 20 years, the same as for the control and conversion equipment. In 20 years of operation the wind generator could require some maintenance operations, especially on the bearings and, if present, on the breaking system (air compressor, pincers, etc). Anyway, the expected life of an hybrid power plants can be considered of 20 years.

The battery expected lifetime is usually indicated by the manufacturers in number of cycle at a certain Depth of Discharge (DOD) and in standard operating conditions. The expected lifetime of batteries increases if the DOD of the cycle is reduced, thus it can often be convenient to oversize the battery bank nominal capacity in order to discharge it always at low DOD and to increase its expected lifetime. It must also be taken into account that if the batteries are working at ambient temperature higher than 20°C their expected life time decreases and approximately it goes halves every 10°C of temperature increment. Also the quality of the electrical voltage and current supplied to the batteries can affect its expected lifetime: a high frequency ripple in the battery current, coming from the battery converter or the others converters in the system can accelerate the battery ageing. If the batteries are charged following the optimal cycles indicated by the manufacturer (V-I curve) and are not periodically treated with a full charge/discharge cycle, their expected lifetime can be shorter than the one indicated by the manufacturer at rated condition.

As the battery lifetime depends on many conditions that can't be known in advanced, it can be seen that it's quite complicated to evaluate the exact number of batteries replacement that must be taken in place during the whole life of the hybrid system. A rough calculation can be done assuming that batteries will undergo a charge/discharge cycle each day with a maximum DOD of 30%. In this case one can expect from gel lead-acid batteries (the most performing technology for sealed lead acid batteries in stationary applications) a lifetime of 4000 cycles in standard conditions, that can be shortened to 2000 cycles considering the high operating temperatures, the high frequency ripple on the battery current and the non optimal charging and discharging operations. Considering one charging/discharging cycle each day, during the entire life of the hybrid system the batteries will need to be replaced at least 3 ÷ 4 times.

As the batteries have a very high cost and are difficult to transport, a very efficient way to reduce the cycle cost of the hybrid system is to adopt solutions that protect the batteries form excessive stress (thermal stress, cycling stress, electrical stress) in order to prevent them from premature ageing. It could be found that more complex battery converters, that can have a higher initial investment cost, are able to reduce the ripple on battery current, so reducing the number of battery replacements required and, consequently, reducing the life cycle costs of the system.

The number of charging/discharging cycles on the batteries can be reduced not only through a proper sizing of the renewable generators and of the storage system, but also by

adopting appropriate power flow control algorithms. Regarding these problems there is not a big difference between the DC or the AC bus configuration. More differences can be found in considering the limitation of the high frequency ripple that can be achieved in the two different configurations, also taking into account the possibility to eliminate the battery converter on DC bus configuration.

5. Hybrid renewable generation units in grid connected mode

The aspects concerning the introduction of small renewable generation units dispersed on the territory into the low voltage (or medium voltage grid) is analysed in the literature under the general subject of "Dispersed Generation". The main problem concerning the dispersed generation is how to integrate a growing number of dispersed renewable generation units with the grid, without causing problems to the grid stability and to the grid regulation and protection system. The main solution to this problem is to adopt the Smart Grid configuration. Several definition exist in literature of the Smart Grid concept, depending on the aim of the author and on its point of view on the system. In general one Smart Grid can be considered as small low voltage (rarely medium voltage) grids including some dispersed generation units, some loads and at least a storage system, equipped with a communication system that are able to be connected to the low voltage (or medium voltage) grid or, possibly, to work in stand alone configuration. Whether they are integrated in a Smart Grid or connected to the low voltage grid, dispersed renewable generation units can support the Power Quality of the grid supply. To achieve this purpose, the main condition is to equip the renewable generation units with storage systems. Secondarily, to improve further the benefits of dispersed generation on power quality of supply, it can be needed to provide the renewable generation units with a communication system.

In the following sections, for generality purpose, hybrid generation units equipped with a battery storage system will be analysed. In particular the effects of this dispersed renewable generation units on the different power quality requirements will be examined and some design solutions allowing to improve the performances of this systems will be presented.

In the following the main concepts of Power Quality regulation in grid connected systems are analyzed, focusing on how small hybrid generation units, connected on the LV (or MV) grid, can affect them.

Most of the solutions reported below are currently not feasible for LV and MV public networks, that aren't designed to accept active loads, such as renewable generation units. Anyway, as many studies and test sites are being put in place and it seems to be a common will to modify the LV and MV networks structure and management in order to make them able to accept an increasing number of diffused generation, the following analysis will be carried on considering that the MV and the LV network are able to accept and to actively interact with an indefinite number of small hybrid generation units.

Currently, diffused generation units connected to MV and LV networks are required to maintain a "passive behavior", in the sense that they must inject in the grid only the active power available from the sources and separate themselves from the grid whenever a deviation from the nominal values of grid voltage or frequency occurs, that is whenever a problem on the grid appears. In this conditions, diffused generation units can't improve the existing power quality level, they can only avoid to worsen it, by controlling their injected current harmonic content and, eventually, by reducing their output power variations. To increment the Power Quality level of the LV and MV grids, diffused renewable generation

units should be enabled by the standards and by appropriate changes on the grid structures, to have an active role. For example small generation units should be allowed to produce also reactive power and to support the grid in case of grid faults. To achieve this result many studies are being done on the network, to individuate possible problems correlated to the injection of active and reactive power in MV and LV nodes, and to solve them by an adjustment of the grid regulation (voltage and frequency regulations should be coordinated with the diffused generators) and protection system (the presence of diffused generators can cause the inversion of some current fluxes and may generate problems during the automatic reclosure operation of MV breakers). In the following the solutions to be adopted on MV and LV network to include diffused generators in their regulation structures will not be considered, but it will be assumed that this solutions will be implemented. The attention will be focused on the diffused generators side, trying to understand which are the principal features that must have diffused hybrid generation units in order to support and increase the Power Quality level of modified MV and LV networks. From these considerations some design constraints will follow, and they will be analyzed in the next section.

It must be noted that all the following considerations are referred only to small diffused hybrid generation units, to be connected on LV and MV network. The big renewable power plants connected to HV, usually big wind power plants, are not considered.

5.1 Requirements on voltage waveform

Usually the voltage regulation on public grids is made at the High Voltage and possibly even at the Medium Voltage level. In Italy, for example, the last step in voltage regulation is made in the primary substation (HV/MV substation) by setting the tap changers of the HV/MV transformers. Because of the voltage drops in the MV and LV lines, the voltage level on LV distribution network can vary from values close to the rated one near the secondary substations, to values close to the minimal admitted threshold at the end of long LV lines in high load conditions.

Usually, because of the predominantly inductive behaviour of the line impedances, the voltage and frequency regulations can be decoupled in such a way that grid nodes voltage levels are controlled by acting on the reactive power fluxes and the grid frequency is controlled by acting on the active power injections in the grid nodes.

Diffused renewable generation units connected to the low voltage network can cause unexpected local increments of the voltage level. The effect of the diffused generation units on the grid voltage depends on many aspects such as the generation unit size and position along the LV line and the power factor of the complex power injected in the grid. Nowadays in Italy there is no possibility to regulate the power factor of small renewable diffused generation connected to the LV grid, as it's stated that all the generation units connected to the LV grid must have an output power factor equal to 1 (only active power injection). Independently from the grid national rules, that will evolve together with the technical developments, the only way for diffused generation units to assist the voltage regulation in the LV network is to control the reactive power injected in the grid.

The hybrid power plants analyzed in this chapter can contribute to the improvement of voltage profiles on the LV and MV networks and can be actively involved in the grid voltage regulation only if they are able to regulate their reactive power injection in the grid.

Looking at the voltage regulation operated nowadays on the big power plants connected to the HV network, one can imagine that the voltage regulation on the MV and LV diffused generators could be organized in, at least, two steps: primary voltage regulation and secondary voltage regulation.

Each generator participating to the **primary voltage regulation** reacts to any node voltage variations with a change in its output reactive power. The relation between the output power variation and the voltage variation that causes it is called *statism*, and has a different value for each generator. A solution to apply the primary voltage regulation on the diffused generators could be to introduce a regulation statism also in each renewable generation unit, in such a way that its output reactive power changes depending on the grid voltage variations (droop control for microgrids). The droop control is implemented directly in the interface converter and the statism value can be calculated by the generation unit control system or can be imposed by an external higher level supervisor. The maximum current value of the interface converters limits the global complex power that the generation unit can inject in the grid. Thus, the reactive power set point should be coordinated with the active power set point resulting from the frequency regulation, not to exceed the current limit of the converter interface. If the reactive power statism is settled directly by the generation unit controller, it will be its duty to coordinate the active and reactive power set points. If the statism is imposed by an external supervisor, the hybrid power plant must send to it the information regarding its actual state (actual current, current limits of the converter, sensible component temperature,...), and the external supervisor will correct consequently the statism value of the power plant, taking into account the information received by all the diffused generators of a certain area. In this case a communication system is needed to implement the primary regulation, but the hybrid generation units of an area can be coordinated together and a more precise primary voltage regulation can be achieved. The **secondary voltage regulation** is implemented by the external supervisor, after an action of the primary regulation, by sending to each power plant the variation in the reactive power production. The secondary voltage regulation has the aim to avoid the circulation of reactive power fluxes between generation units.

In this case a communication system is necessary between the central supervisor and the hybrid generation units of an area. The hybrid power plants send to the supervisor the information regarding their actual state and the external controller calculate consequently the reactive power injection variation of each generation unit.

The reactive power that can be injected or absorbed by a hybrid generation unit doesn't depend on the energy availability from the sources nor on the state of charge of the battery bank, as the energy available from the renewable generators and from the storage is active and not reactive energy. To supply a certain value of reactive power, the hybrid generation unit needs to absorb a minimal amount of active power sufficient to cover its global internal losses (losses in the converters, on the wirings, in the passive components, ...) and the supply of the electronic control system (electronic boards, sensors, relays,...). This minimum active power can be provided by the renewable sources or by the battery bank or even, if the interface converter allows it, can be absorbed by the grid. In this third case, the hybrid generation units can provide the reactive power required by the grid even if there is not at all availability of active power neither from the renewable sources nor from the storage system.

If the minimum active power needed for the power plant operation is guaranteed, the reactive power injected (or absorbed) by the hybrid generation unit is limited only by the

sizing of its components. The current circulating in each component should not over goes the maximal design value, thus the output active and reactive power of the hybrid system are limited in order to respect this condition.

In the design of the grid connected hybrid power plants it should be taken into account the maximum output current that can be supplied, considering both the active and the reactive contribute.

What explained about the voltage regulation concerns the hybrid generation units with a **DC bus configuration**. When this generation units are connected in parallel to the grid, they have only one interface point (interface converter) that can supply reactive power to the grid.

If the hybrid generation units have an **AC bus configuration**, all the source converters and the storage converters of all the power plants are connected in parallel on the grid, that can be seen as a common extension of all the AC buses. In this case all the grid connected converters can supply reactive power to the grid, within the limits of their maximum rated current. It's a design choice to decide which converters are enabled to participate to the voltage regulation, and if the converters will receive directly the reactive power set point from the external regulator or if the external regulator will send a global reactive power set point for the entire generation units and then the generation nit internal controller will split the reference reactive power value to each converter.

5.2 Requirements on voltage frequency

Unlike the voltage amplitude, the voltage frequency is a global variable, that is the same for all the grid nodes. As said before the voltage regulation is correlated to the active power, in particular, if the total active power injection in the grid nodes is equal to the total active power absorbed by the loads, the grid frequency remains constant. If the active power injected in the grid nodes is higher than the active power absorbed, the grid frequency increases, and vice versa. Hybrid distributed generation units could contribute to the grid frequency regulation, as they are able to regulate the active power injected in the grid and they can also absorb active power and store it in the battery bank. Actually, the contribution of a single hybrid generation units is irrelevant among the total amount of active power exchanged in the grid nodes, thus a variation in the active power supplied by a single hybrid generation unit wouldn't have any effect on the grid frequency. Only if the number of diffused generators is relevant and if all the generation units are coordinated by a higher level supervisor, the diffused generation can have an impact on the grid frequency regulation. Each generation unit must be equipped with a communication system that enables it to receive from the grid operator the active power reference values, and it must guarantee a certain active power availability to follow the reference set point. Looking at the frequency regulation operated nowadays on the big power plants connected to the HV network, one can imagine that the frequency regulation on the MV and LV diffused generators could be organized in at least two steps: primary regulation and secondary regulation.

Each generator participating to the **primary frequency regulation** reacts to any frequency variations with a change in its output active power. The relation between the output power variation and the frequency variation that causes it is called *statism*, and has a different value for each generator. A solution to apply the primary frequency regulation on the diffused generators could be to introduce a regulation statism also in each renewable generation unit, in such a way that its output power changes depending on the grid

frequency variations (droop control for microgrids). The droop control is implemented directly in the interface converter and the statism value can be calculated by the generation unit control system or can be imposed by an external higher level supervisor. It could be useful to adapt the statism value to the energy availability of the system: in case of a grid frequency reduction, a hybrid generation unit with a low energy availability will react with a lower increase of the injected power than a hybrid generation unit that have the battery fully charged. If the statism is set directly by the generation units controller, it will be its duty to calculate the energy availability of the system and adapt consequently the statism and no communication system is required in this case for the primary frequency regulation. If the statism is imposed by an external supervisor, the hybrid power plant must send to it the information regarding its actual state (battery state of charge, current availability of renewable sources, weather forecast...), and the external supervisor will correct consequently the statism value of the power plant, taking into account the information received by all the diffused generators of a certain area. In this case a communication system is needed to implement the primary regulation, but the hybrid generation units of an area can be coordinated together and a better exploitation of the renewable sources can be performed.

The **secondary frequency regulation** is implemented by the external supervisor, who send to each power plant the variation in the active power production necessary to bring the grid frequency to the nominal value after an action of the primary regulation. In this case a communication system is necessary between the central supervisor and the hybrid generation units of an area. The hybrid power plants send to the supervisor the information regarding their actual state and the external controller calculate consequently the power injection variation of each generation unit.

It must be noted that unlike the traditional power plants, the hybrid generation units can also absorb active power from the grid. This working condition is possible if the interface converter is bidirectional and if the control system is enabled to manage this condition. One could think to exploit this characteristic, as it allow a larger range of active power regulation. For example it could useful to set two different value for the positive statism, that regulates the positive output power variations, and the negative statism, that regulates the variations in the active power absorbed by the generation unit. In this way generation units with a low battery state of charge can be controlled to react with a low injected power increment if the grid frequency decreases, and with a high absorbed power increment of the grid frequency raises. This kind of control can improve the battery management and the overall system coordination, but need a very strong coordination of the diffused generation unit, to avoid the condition where some generation units are discharging their batteries in the grid and some other generation units are absorbing active power to recharge their storage system. This exchange of active power between the storage systems is an unwanted condition because it leads to an great waste of energy caused by the charging and discharging efficiencies of the storage systems.

To guarantee the capability to participate to the primary and secondary frequency regulations, the generation units should keep a **primary and secondary active energy reserve**. This energy reserve can be stored in the battery bank of the hybrid generation units, by setting some threshold on the battery state of charge. The entity of the frequency regulation reserve must be fixed during the designing process together with the network operator, depending on the size of the power plant.

The value of the active energy reserve that must be guaranteed in the hybrid generation units in order to participate to the primary and secondary frequency regulation affects the size of the storage system and the size of the renewable generators. The storage system must be able to contain an energy at least equal to the sum of the two regulation reserves and the renewable generators must be able to supply enough active power for the ordinary operation and for recharge the storage system with a periodicity depending on the frequency of the frequency regulation operations.

What explained about the frequency regulation concerns the hybrid generation units with a **DC bus configuration**. When this generation units are connected in parallel to the grid, they have only one interface point (interface converter) and they can maintain the same internal power management algorithm used for the islanded operation. So, the interface converter follows the active power set points coming from the frequency regulation and the generation converters extract the maximum power available from the renewable sources (or limit this power to a set point value) and the battery converter maintains the energy balance on the DC.

If the hybrid generation units have an **AC bus configuration**, all the source converters and the storage converters of all the power plants are connected in parallel on the grid, that can be seen as a common extension of all the AC buses. In this case the renewable generator converters operate as current generators, injecting in the grid the maximum power available from the sources, or, if they can work in RPPT mode, limiting the injected active power to a certain set point given by the generation unit supervisor. The storage system converters perform the voltage and frequency regulation on the grid, as the interface converter does for generation units with DC bus configuration. The external regulator has the same functions than in the case of DC bus configuration plants. The coordination of the renewable generators and the battery bank of each power plant is demanded to the power plant general supervisor, which, for example, sends active power set points to each renewable source converters when the RPPT operation is needed. Moreover each power plant general supervisor should send to the external regulator information concerning the present availability of the renewable source and, possibly, the weather forecasts. Thus, even if in AC configuration all the converters of the power plants seems to be independently connected to the grid, the interface between each hybrid power plant and the external supervisor is made only by the power plant general controller, and not by each converter separately.

In the case of AC bus configuration the problem of active power circulation between storage systems is much more relevant than for Dc bus configuration. When all the storage systems are connected in parallel to the grid, they must exchange active power in both direction with the grid, which means that the battery can absorb power indistinctly from any other generator connected to the grid, even from the other storage system operating in discharging mode. The only way to avoid the exchange of active power between storage systems is that the external supervisor disables the charging of all the batteries when there is at least a storage system in discharging operation. This solution is, not feasible, or, at least very restrictive, thus, a rate of active power exchange between storage systems have to be accepted in parallel operation of AC bus generation units.

6. Design aspects of HGDU in grid connected mode

As highlighted previously, the Power Quality in grid connected systems can be supported and improved by an active participation of the diffused renewable generation units. On the

following three main aspects of the design of renewable hybrid power plants for grid connected operation will be analyzed, trying to point which are the possible choices that leads to a higher power quality of supply.

6.1 Sizing

The sizing of renewable generation units is the aspect that mostly affects their capability to participate to the frequency regulation (primary and secondary regulation reserve) and the voltage regulation (high current injection in case of voltage dips), to supply grid services (peak shaving and load leveling) and to guarantee the preferred loads continuity of supply during grid black outs. In grid connected systems the sizing of hybrid diffused generation units is based on technical-economic optimization. Unlike islanded systems, in grid connected generation units it's possible to evaluate the price of the active power (and possibly also reactive power) produced, depending on the kind of services the generation unit offers. One can imagine that in the future the produced energy will be differently paid, in function of its contribution to the grid power quality: for example energy produced in peak shaving operation should be rewarded at a higher price than energy produced in low load hours. Moreover, also grid services not directly correlated to the production of active power, such as the valley filling and the reactive injection to regulate the grid voltage, should be paid, in agreement with the network operator. The initial investment cost should be compared to the revenues coming from the active energy sale and from the supplying of all grid services.

Sizing constraints

As said before, the sizing of grid connected hybrid generation units must be done comparing the overall cost of the hybrid system with the revenues coming from the sale active energy and of grid services to the network operator.

As for the islanded systems, the overall cost of the system is made up of two contributions: the initial capital investment and the maintenance cost. The initial cost is strictly related to the size of the renewable generators and of the battery bank. The main contribution to the maintenance cost is due to the battery replacements during the lifetime of the system, that is usually much longer than the battery lifetime. Globally, the battery cost, that depends on the battery nominal capacity, has a great impact on the total cost of the system, as it affects both the initial investment and the maintenance cost.

Together with the network operator it should be decided the active energy price in normal conditions (normal supply to the grid) and in case of grid services (active energy supplied during for peak shaving, for load leveling, to guarantee the supply of privileged loads during grid break down, ...). Then, the hybrid system designer should decide which services provide to the grid and the system sizing is calculated consequently.

A possible strategy for the hybrid system sizing, considering the different grid services to supply is presented in the following.

The grid services requiring an injection (or absorption) of active power affect the renewable generators and battery bank sizing. To the design of the hybrid system it's necessary to get an estimated curve of the active power required to the generation unit by the grid, in order to comply the grid services performances established at the beginning of the project. The estimation of this curve is the most difficult part of the project and is a necessary step, as it allows to correctly size the storage system and the renewable generators. For the peak shaving, load leveling and frequency regulation services, it can be planned, together with

the grid operator, the expected curve of active power required to the generation unit. This curve can be considered as the equivalent of the load demand profile for the islanded systems, as it represents the minimum active power supply that should be guaranteed by the generation unit. An index can be calculated for the grid connected systems, analogue to the LPSP for the islanded systems, in order to define the capability of the hybrid generation unit to satisfy the grid services guaranteed at the beginning of the project. In the following this index will be referred as LGSP (Loss of Grid Service Probability). As for the islanded systems, the LGSP can be calculated as:

$$LGSP = \left(\sum_{i=1}^N \int_{\Delta_{SI,i}} P_{gs_NS,i}(t) \cdot dt \right) / E_{gs_tot} \quad (11)$$

where N is the number of failed service supply to the grid in one year;

Egs_tot is the total active energy required to fulfill the grid services guaranteed to the grid operator;

Pgs_NS,i is the power not supplied during the failed ith service supply period

SI,i is the duration of each service supply interruption.

The design value of LGSP is chosen by the hybrid generation unit designer, on the basis of the economical compromise between the overall cost of the system, the revenue from the grid service supplying, and the penalties to be paid in case of loss of grid service supply. It should be noted that in grid connected systems, the over sizing of the hybrid generation unit is not critical, as, except for special conditions of very low load demand, the excessive energy produced by the generation units can always be sold to the grid, even if its price can decrease when the energy need of the grid is low. Consequently, a reasonable design choice could be to fix the LGSP desired value to zero. From this condition the minimal size of the renewable generators and of the storage system can be derived.

The second step is to verify the need of adding a high power storage system to supply high active power peaks to the grid, for example in case of peak shaving service.

If the renewable generation unit must guarantee the continuity of supply to some privileged loads, it should be verified if the energy capability of the hybrid system is enough to guarantee the loads supply during the maximum expected duration of grid interruptions. If the energy capability of the system is not enough, the renewable generators and in particular the storage system sizes should be increased.

It should be noted that the concept of wasted energy changes from islanded systems to grid connected systems. In grid connected systems the produced energy can almost always be sold to the grid, and so the rate of wasted energy can be considered always zero. A real waste of energy can occur when the hybrid system must provide a valley filling service. In this case, when the load is low the hybrid generation units must absorb power from the grid and store it into the battery bank, and the renewable generators must be shut down. During the valley filling period, all the energy available from the renewable sources is not converted and is wasted energy. It must be said that usually the load demand is very low during the night, that is when the photovoltaic source is not available, so the wasted energy in grid connected system is very low and the economical drawbacks of a system over sizing are less relevant than in the case of islanded systems. It must be noted that if the hybrid generation units must provide a valley filling service, the storage system must be properly managed, in order to be able to store the energy absorbed by the grid during the valley filling operation. If the battery are fully charged when the valley filling is required, the

energy absorbed from the grid will be dissipated in the breaking resistance of the hybrid power plant and is, actually, wasted energy. If no breaking resistance is included in the hybrid generation unit, the valley filling service can be provided only if the battery state of charge is low enough to enable the storage of all the active energy that is required to be absorbed from the grid.

The considerations written above refers to the energy sizing of the renewable generation unit. The power (or thermal) sizing is calculated considering the maximum active power peak and the maximum reactive power peak that the hybrid generation unit will be required to supply to the grid, and their contemporary probability. The maximum active power peak is presumably due to the peak shaving operation, while the maximum reactive power peak is usually caused by the voltage regulation in case of a significant voltage amplitude reduction (voltage dip).

6.2 Plant configurations

There are many different power plants configuration, that can differ by the nature of the renewable sources, by the type of the hybrid storage system and by the kind of converters used. The different hybrid power plants configuration are usually classed in function of the nature of the power bus (AC bus at frequency line, DC bus or high frequency AC bus).

The main choice to be made regarding the hybrid plant topology, as for islanded systems, concern first of all the type common power sharing bus (DC or AC bus) and, secondly the topology of the static converters dedicated to the sources and to the battery bank.

Some of the aspects considered for the islanded system regarding the DC bus or the AC bus consideration are still valid also for grid connected systems, such as the consideration regarding the modularity and the overall costs. Some other considerations, listed below, should be modified and adapted to the grid connected hybrid power plants.

Kind of loads and sources. Grid connected generation units must supply grid frequency AC voltage (or current) both in grid connected and in transient islanded operation in case of grid break down. If the sources are AC generators (doubly fed or synchronous generators) and the storage system is made by electrochemical batteries, then a line frequency microgrid may be a better system since the grid can be directly connected to the AC bus, thus eliminating the DC/AC interface converter.

Control system. For the internal control system of each hybrid power plant, the same consideration made for the islanded systems can be referred also for the grid connected configurations. Converters on a DC bus system tend to be simpler than those on a AC bus system, and the control for a DC bus system is simplified since frequency control and reactive power internal fluxes control are not a consideration. In AC bus systems both active and reactive power internal flow should be controlled, monitoring both the amplitude and the frequency of the AC bus voltage. Moreover, the phase shifting between voltage and currents should be monitored in order to control the power flow direction.

Some more considerations should be done regarding the external control system needed to coordinate the operations of several hybrid generation units grouped in a so called "smart grid" and connected in parallel to the grid. As explained previously, this coordination control is necessary in order to enable the diffused generation units to participate to the grid voltage and frequency regulation and to provide grid services.

For **DC bus configuration** systems connected in parallel with the grid, the only interface toward the grid and the other generation units is always the interface converter. The hybrid

generation units receives active (P) and reactive (Q) power set points from the external smart grid regulator or from the internal droop control implemented for the voltage and frequency regulations. The interface converters implements the P and Q set points and the generation unit internal energy balance is maintained by the storage converter, by controlling the DC bus voltage. The internal control of the hybrid power plant is not affected by the external system, but it goes on working with the same logic both in grid connected operation and in back up islanded operation. Moreover, when the generation unit is working in back up islanded operation it makes no difference for the energy balance regulator if the generation unit is in single islanded configuration or in parallel with other generation units forming an islanded microgrid configuration. Thanks to the interface converter and its regulator, there is a complete decoupling between the internal hybrid power plants system and the external system that is the grid, in grid connected operation, or other generation units and the privileged loads, in back up islanded operation.

In **AC bus systems**, all the generation units converters are connected in parallel to the grid. The hybrid generation units receives P and Q set points by the external smart grid regulator or by the internal droop control implemented for the voltage and frequency regulations. The renewable generator converters, in normal operating conditions, inject all the active power available into the grid. The battery converter injects the reactive power required by the Q set point and injects or absorb the active power equivalent to the difference between the P set point and the total power produced by the renewable generators. When the AC bus system passes in the back up islanded operation only the storage converter control changes its operation, while the renewable converters are not sensitive to the change in the external system configuration, as for the DC bus configuration.

The main difference between the DC bus and the AC bus configuration concerning the control system is related to the active power exchange between storage systems of different generation units connected in parallel to the grid or forming an islanded smart grid during the back up operation. If the hybrid generation units are not required to provide the valley filling service (that is to absorb active power when the load demand is low) for the DC bus systems the circulation of active power between storage systems can be avoided by using unidirectional interface converter. In such a way the active power flux is always directed toward the grid and the battery bank of each generation unit can be recharged only by the renewable generators of the power plants. If the valley filling operation is required, the interface converters must be bidirectional and the only way to avoid the exchange of active power between storage systems is that the external smart grid controller blocks the charging of any storage system when there is at least one storage system in discharging operation. Usually, all the generation units of a smart grid are coordinated to provide the same grid service, as their single active or reactive contribution would not be perceived by the grid, given the small size of the diffused generation units among the grid inertia. It can be considered that all the hybrid generation units connected to a smart grid, and referring to a single external controller, will be operating in valley filling mode at the same time, thus all the storage systems will be in charging operation at the same time and they will not exchange power. In all other working conditions different from the valley filling, the interface converter will be controlled to allow an active power flux only directed toward the grid, in order to prevent the active power exchange between the battery banks.

In the AC bus configuration all the battery converters are in parallel on the grid and they are necessarily bidirectional, to allow the charge and discharge of the batteries, even if the

valley filling service is not required. To avoid the exchange of active power between storage systems, the external smart grid controller should prevent the charging of any storage system when there is at least one storage system in discharging operation. This control technique is very binding and requires a continuous monitoring of the storage system operation in every working condition of the generation units, and not only during the valley filling operation as for DC bus systems. The only alternative several for AC bus parallel connected generation units is to accept a rate of active power exchange between storage systems.

From what explained above, It can be stated that the DC configuration is preferable regarding the external coordination of several hybrid generation units connected in parallel, as the interface converter ensures a complete decoupling between the internal system of the generation unit and the external system (grids and other generation units connected in parallel).

Efficiency. As for islanded systems, the global efficiency of the grid connected generation units depends on many aspects: renewable source peak power related to the loads rated power, number and typology of converters, and power flow management. The considerations made for the islanded systems can be referred also for grid connected generations units, by adding the following comments.

One of the main cause of power losses in the system is the storage battery bank, thus, the overall efficiency of an hybrid system is affected by the rate of active energy that has to be stored in the battery bank before being delivered to the grid. The rate of the stored energy can be reduced by optimizing the internal power flow management algorithm and by the choice of the grid services that the renewable generation units provides.

In AC bus configurations transformers can be used to adapt generating units and storage system voltage level to the LV or MV grid voltage. In DC systems, additional conversion stages could be required to raise the output voltage of generation units and the storage system, or the system can be managed at low DC voltage, with no additional conversion stage but with an output transformer between the DC/AC interface converters and the grid. The efficiencies of the additional conversion stages and of the transformer should be evaluated for different operating conditions of the generation units.

Generally, for medium size generation units connected to the MV grid, the transformer is necessary in both the configurations, to rise the power plant output voltage to the MV grid level.

Reliability. In AC bus systems the critical component is the battery converter. Usually the battery converter implements the active and reactive power regulation to provide the grid services (peak shaving, load leveling,...) and to participate to the voltage and frequency regulations.

If the battery converter breaks down, the renewable generator converters can go on feeding active power into the grid, but the active power can no longer be regulated by the storage system, as require provide grid services and to participate to the power and voltage regulation.

In DC bus systems there are two critical components: the interface converter and the battery converter.

If the interface converters breaks the hybrid generation units is separated from the grid and the loads and can no longer supply neither reactive nor active power.

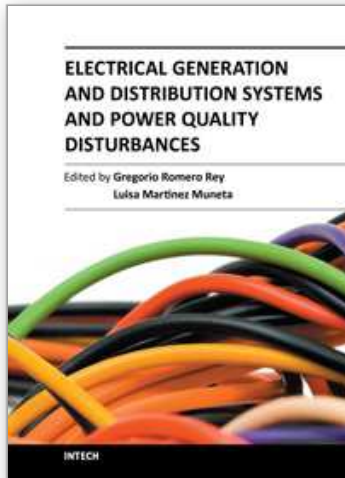
The battery converter maintains the power balance between the active power injected into the grid and the active power generated by the renewable sources If the battery converter

breaks down, the renewable generator converters can go on feeding active power into the DC bus, but the active power balance is no longer maintained on the DC bus. The generation unit can go on supplying into the grid the active power available from the renewable sources only if the interface converter control changes its operation. If the battery converter doesn't work anymore, the interface converter must maintain the energy balance on the DC bus, by regulating the output active power in order to maintain the DC bus voltage to its nominal value. It's not very reasonable to contemplate this working condition, as the system is not providing grid services and needs to be repaired. Thus, it can be stated that the DC bus generation units can't inject any power into the grid when the battery converter breaks down, even if the interface converter is still working.

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The utilization of renewable energy sources such as wind energy, or solar energy, among others, is currently of greater interest. Nevertheless, since their availability is arbitrary and unstable this can lead to frequency variation, to grid instability and to a total or partial loss of load power supply, being not appropriate sources to be directly connected to the main utility grid. Additionally, the presence of a static converter as output interface of the generating plants introduces voltage and current harmonics into the electrical system that negatively affect system power quality. By integrating distributed power generation systems closed to the loads in the electric grid, we can eliminate the need to transfer energy over long distances through the electric grid. In this book the reader will be introduced to different power generation and distribution systems with an analysis of some types of existing disturbances and a study of different industrial applications such as battery charges.

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