UNWANTED ISLAND MAINTAINING IN LV GRIDS: ANALYSIS AND POSSIBLE SOLUTIONS. A STUDY BASED ON THE REAL-TIME DIGITAL SIMULATOR

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ABSTRACT

Islanding refers to the condition in which one or more distributed generators continue to power a section of the network even though grid power from the electric utility is no longer present. Unwanted islanding can be dangerous to utility workers, who may not realize that a circuit is still powered. Furthermore, because the present electrical systems are not designed to work under these condition, the unwanted isle is uncontrolled with reference to protection system in case of fault, rated values of voltage and frequency. Finally, reclosing the circuit onto an active island may cause problems with the utility's equipment.
For that reason, a smart grid must prevent islanding or detect it and immediately clear the situation.
In this work the unwanted island generation and maintaining are analyzed for a 4-wires LV grid composed by a mix of generators and loads. Both single-phase and three-phase generators are considered, in order to have an unbalanced grid with realistic topology. Analysis is performed using the Real-Time Digital Simulator (RTDS) installed in the Enel Test Center of Milan.
The purpose of this work is to evaluate the real risk of islanding, analyzing different scenarios and taking into account transitory phenomena and capability limits of generators.

INTRODUCTION

It is well known that a large amount of Distributed Generation (DG) produces problems on Distribution and Transmission grids in terms of voltage and frequency values. Network voltage is influenced by DG active/reactive power injections in MV and LV grids. Frequency variations can happen in case of imbalances between load and generation in the national grid, due to network problems or misevaluations in the control procedures; the high penetration of renewables, that can have fluctuations in the injected power, increases the probability of these events.
In order to mitigate the situation, National Regulators, under the pressure of Transmission System operators, have defined new operational rules for DG. Typical automatic functions introduced in Italy in the last month are:
- Volt/VAr regulation (Q-V), for voltage control
- Active power drop-based frequency regulation (P-f), for frequency control.

Thanks to this Volt/VAr regulation, the reactive power exchanged between DG and grid, or DG power factor, is regulated according to the delivery point voltage, to limit voltage variations. In the active power drop-based frequency regulation, the generated active power is regulated according to grid frequency, to stabilize the power system.
In Italy the voltage regulation, for DG connected to the LV grid, is defined by the Italian Technical Standard CEI 0-21 [1] while the frequency regulation is defined by the “84-12 Deliberation” of the Italian Electrical Energy and Gas Authority (AEEG) [2].
However, both voltage and frequency regulations, created to stabilize the national grid, have the secondary effect of stabilizing the unwanted islanding situations.

THE UNCONTROLLED ISLANDING

In certain situations in active LV network, if a feeder breaker is opened, isolating the network located downstream, the frequency of the isolated circuit (island) derives so as to reach a steady-state value which typically depends on the active power imposed by the loads to DG. Network voltage follows a similar behavior: its steady-state value, depends on the reactive power imposed by the loads. Frequency and voltage variations depend on the dynamic behavior of loads and DG.
It is important to note that DG dynamics exist also if the generators are based on power electronic converters (e.g. solar or wind distributed generators). In this case, dynamics are determined by active and reactive power regulators and by frequency/phase meters (typically PLL- Phase-Locked Loop), equipping the relevant inverters.
In order to clarify the consequent islanding, we can analyze frequency variation phenomena in the simple system represented in Figure 1. The described approach is based on several hypothesis (hp1, hp2, hp3 and hp4) which allow a simple analysis, without impacting the generality and the validity of the results. With this model it is possible to mathematically calculate the islanding frequency value. In the picture we have a grid-tie inverter regulated with a power-frequency drop function. The active power proportional integral (PI) regulator acts on the inverter voltage phase shift [3].
The reactive power PI regulator acts on inverter voltage amplitude. In the P-f drop block “A” represents the so-called frequency dead-band and “B” represents the drop band. Normally the inverter works in the frequency dead band and the MPPT algorithm is enabled, but when there is a frequency drift, the systems works in the drop band and the Maximum Power Point Tracking (MPPT) algorithm is disabled.

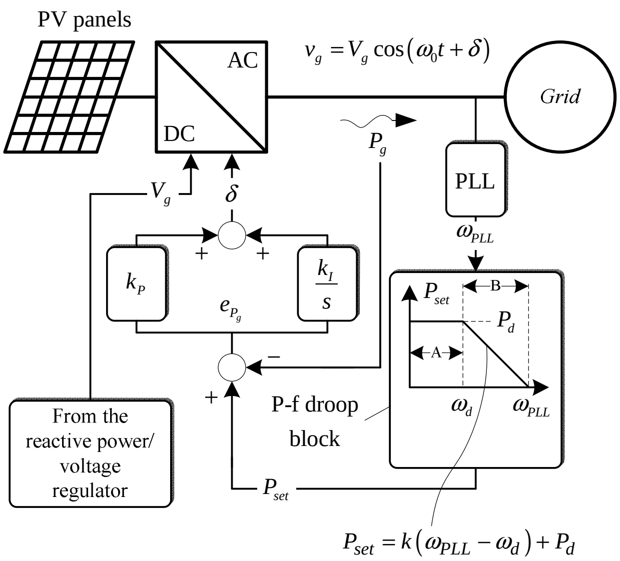

Figure 1. The considered inverter based DG.

The inverter voltage at the delivery point is:

$$v_g = V_0 \cos(\omega_0 t + \delta) = V_0 \cos \vartheta_g \qquad (1)$$

where V_0, ω_0 and δ are respectively the modulating wave amplitude, angular frequency and phase shift. When the angular frequency ω_0 is considered as constant and equal to the rated value (hp 1), a frequency drift is possible only thanks to the δ phase shift variation.

The PLL measures the dynamic phase ϑ_g, providing the angular frequency ω_{PLL} (a PLL is used as a frequency meter). For simplicity (hp 2) the PLL dynamic, typically due to the PI regulator integrated into the PLL, is not considered (the PI "speed" is infinite). Because the PLL measures the derivative value of ϑ_g, it is possible to write:

$$\omega_{PLL} = s\vartheta_g = \omega_0 + s\delta \qquad (2)$$

which represents the PLL transfer function (s is the Laplace complex variable, the Laplace operator).

The P-f drop block transfer function (in the drop band) is:

$$P_{set} = k(\omega_{PLL} - \omega_d) + P_d \qquad (3)$$

where k is the drop constant (in [W/(rad/s)]), P_d and ω_d are respectively drop band active power and angular frequency, (see Figure 1). The active power regulator transfer function is (considering only the integral part of the PI regulator, with gain k_I):

$$\delta = (P_{set} - P_g)\frac{k_I}{s} = \left[k(\omega_{PLL} - \omega_d) + P_d - P_g\right]\frac{k_I}{s} \qquad (4)$$

where P_g is the inverter generated active power. Deriving the phase shif δ from (2) (with the simplification hp3: $\omega_0 \cong \omega_d$, because in the "84-12 deliberation" the values of these quantities are very close toghether (0.3 Hz) [2]) and using it with (3) in (4) we can write:

$$\omega_{PLL} = -P_g \frac{k_I}{1 - k \cdot k_I} + P_d \frac{k_I}{1 - k \cdot k_I} + \omega_0 \qquad (5)$$

If we consider that $k \cdot k_I \gg 1$ (hp 4, because both quantities are typically greater than 1), the previous equation can be rewritten as:

$$\omega_{PLL} = P_g \frac{1}{k} - P_d \frac{1}{k} + \omega_0 \qquad (6)$$

This represents the relation between the generated active power and the grid frequency, when the generator works in the drop band also in islanding (the relation is valid in the drop band independently by islanding).

Equation (6) can be rewritten as:

$$P_g = k(\omega_{PLL} - \omega_0) + P_d \qquad (7)$$

This is identical to (3). In other words the generator's active power-frequency behavior is imposed by the P-f drop characteristic, also in islanding functioning. In this last case, equation (6) allows to calculate the islanding frequency, knowing the active power imposed at generator terminals. If, for example, the generator feeds a single load which absorbs P_L, the frequency working point can be viewed as the interception between the generator characteristic, the equation (6) and the load characteristic.

Figure 2 represents this concept for a constant power load: when the main grid is present, the generator works at the red point and the load works at the blue point. During islanding, the new working point will be the black one, due to the concepts above mentioned, derived by (6).

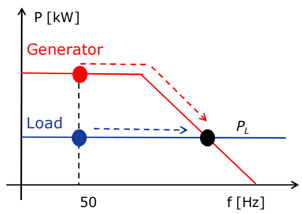

Figure 2. The frequency working point in the island.

As said before, the new working point, in terms of frequency, depends on the active power imposed at the generator terminals.

All these concepts can be also applied to the voltage, considering the regulator of the reactive power in the generator. If this regulator is driven by a reactive power-voltage drop (Q-V), the islanding working point (in terms of voltage) will be the interception between the Q-V generator characteristic and the reactive power imposed at the generator terminals. If, for example, the generator feeds a single load which absorbs Q_L, the voltage working point can be viewed as the interception between the generator characteristic and the load characteristic.

Figure 3 represents this concept for a constant power load: when the main grid is present, the generator works at the red point and the load works at the blue point. During islanding the new working point will be the black one.

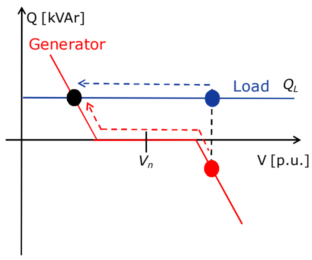

Figure 3. The voltage working point in the island.

Generally, loads' active power also depends on grid voltage, then islanding frequency can be also a function of the grid voltage. In other words, in general, we can write:

$$f_{island} = f\left(P,V\right) \tag{8}$$

From a mathematical point of view the islanding behaviour of a big network is not so easy, due to a big number of equations related each other. In this case simulations represent the practical solution to analyse these phenomena, Removing also all simplifications used in the mathematical model (hp 1, hp2, hp3, and hp4).

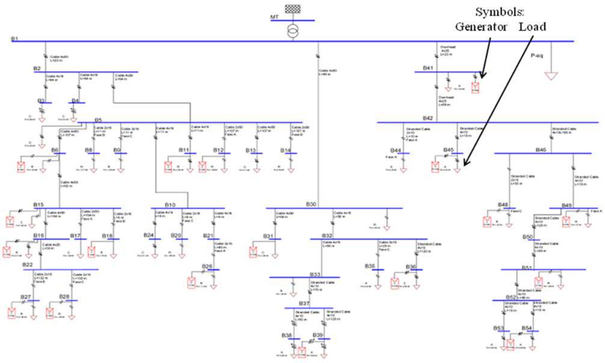

Figure 4. The simulated LV grid.

THE REAL-TIME DIGITAL SIMULATOR

Simulations are performed using the Real-Time Digital Simulator (RTDS) installed in the Enel Test Center of Milan. This fully digital machine, shown in Figure 5, consists of a big number of calculators that work in parallel, in order to numerically simulate the network virtually built in its software environment. Digital and analog simulated values are both available through software-to-hardware interfaces, based on Digital/Analog converters. This important feature allows to connect real devices (like protection relays, regulation and control devices) to the simulated virtual grid. In this way the real power system behavior can be dynamically and completely analyzed in a safety environment.

Figure 5. The Real-Time Digital Simulator (RTDS) in the Enel Test Center of Milan.

THE SIMULATED GRID DESCRIPTION

This study has been realized simulating a three phase network, represented in Figure 4, supplied by a Dy11 MV/LV transformer. Three feeders composes the grid: one urban, one rural and one mixed (urban and rural). Moreover an equivalent load connected to the LV busbar simulates the rest of the LV network.

In order to have an unbalanced grid, both single and three-phase loads and generators are present. The load maximum power (cumulative) amounts 159 kW (power factor PF = 0.9). Loads are represented by the constant P,Q power model. The generated active power (cumulative) also amounts 159 kW, divided into 6 x 10 kW plants (three phase), 3 x 20 kW plants (three phase), 4 x 6 kW plants (single-phase), 5 x 3 kW plants (single-phase).

The generators' active power regulation is frequency-drop based, as stated in the "84-12 deliberation" of the Electricity and Gas Italian Authority (AEEG). Also the interface frequency protections are set according to this standard (wide frequency thresholds, 47.5 Hz to 51.5 Hz). The generators reactive power regulation is voltage-drop based, as reported in the Italian Standard "CEI 0-21". Generators power factor capability is modelled as stated in the "CEI 0-21" standard. Active and reactive power PI regulators implemented in RTDS are represented in

Figure 6. As said before, all simplification hypothesis (hp 1, hp2, hp3, and hp4) have been removed in the RTDS simulations. The angular frequency ω_0 is not constant but is provided by the PLL, then $\omega_0 = \omega_{PLL}$. The PLL, used as frequency meter, is based on the Park Transformation and its scheme is depicted in Figure 7.

In the simulation the electric islanding has been created opening the secondary substation (SS) MV breaker.

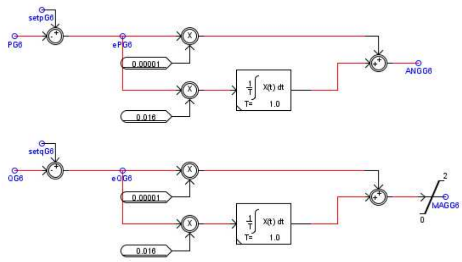

Figure 6. PQ PI regulators in RTDS.

Simulations description

In the study the load has been changed, maintaining constant the generation at 159 kW. After each variation the MV transformer breaker is opened and the islanding maintaining event is checked. Each variation corresponds to the 10 % of the peak power (10 % of 159 kW). For each step the island duration is measured(i.e. the time between the breaker opening and the last generator interface protection tripping.

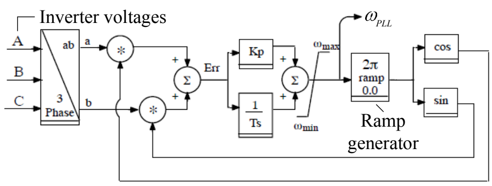

Figure 7. The Park Transformation-based PLL used in RTDS simulations.

In Figure 8 we can see the island maintaining possibility. If the generation is very close to the load (or equal), the island is not stable (in Figure 9 is represented the island duration time). This phenomenon occurs because the reactive load consumption is high and, during the islanding, it must be supplied by generators. Moreover generators must supply reactive power absorbed by LV feeders. Then generators trip due to minimal voltage threshold.
When the generation is higher than the load (see Figure 8 and Figure 9) the islanding becomes permanently stable. Generator feeds the LV grid in terms of active and reactive power. It is important to note that the grid is unbalanced. In fact the Dy MV/LV transformer, opened on the MV side, "turns" and balances the power between phases. Figure 10 and
Figure 11 represent the island voltage and frequency during the islanding steady state.

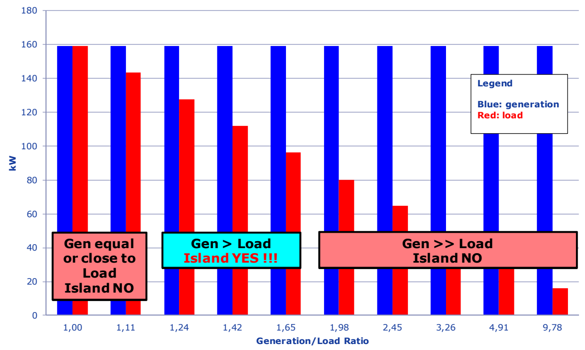

Figure 8. The island maintaining possibility.

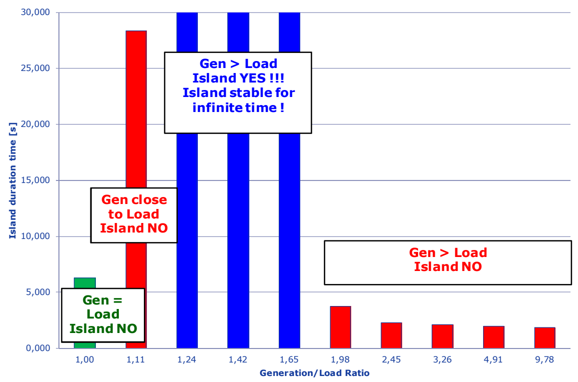

Figure 9. The island maintaining time.

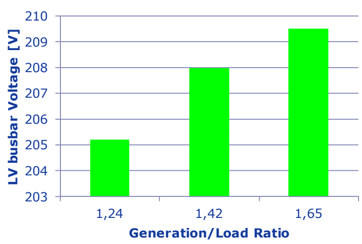

Figure 10. The island steady-state voltage.

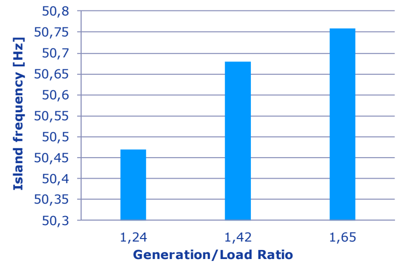

Figure 11. The island steady-state frequency.

Finally, when the generation is very high, compared to the load, the island is not stable (see Figure 8 and Figure 9). This phenomenon occurs because the big gap between load and generation creates a big transient on generator's regulator causing the user interface protections tripping.

CONCLUSIONS

The study reported in this paper demonstrates that the unwanted (or uncontrolled) islanding is possible (in both LV and MV grid). The islanding probability becomes very high when the generators are regulated with drop logics, in terms of active power-frequency (P-f) and reactive power-voltage (Q-V); in fact these logics are designed just for stabilization purposes.
We underline that the islanding steady state, in terms of frequency and voltage, depends on generators and load dynamics. Another parameter influencing it is the load behaviour, as a function of both frequency and voltage.
Moreover the generators (e.g. PV inverters) dynamic depends on the implementation of all the regulations (e.g. the firmware, in case of inverters). Each type of generator (e.g. PV inverter built by different manufacturers) can potentially have a different dynamic behaviour.
From the Distributor point of view, a reliable solution, to avoid the uncontrolled islanding, is the implementation of a remote control system able to clear this possibility. On the MV network, Enel Distribuzione is developing an anti-landing solution based on the remote trip of the generator breakers in case of possible islanding situations.
This approach can also be extended to LV networks taking into account the big extension of this networks and the related costs.

REFERENCES

[1] CEI, 2012, Italian Technical Rule "0-21", *Comitato Elettrotecnico Italiano*
[2] AEEG, 2012, "84-12 Deliberation" of the Italian Electrical Energy and Gas Authority
[3] R. Marconato, 2008, *Electric Power Systems Vol. I, Vol. II, Vol. III*, CEI, Milano, Italy