COMBINED EFFECTS OF DISTRIBUTED GENERATION GRID CODE REQUIREMENTS ON THE TRANSIENT BEHAVIOUR OF ISLANDED SYSTEMS

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ABSTRACT

National and internationals grid codes define the connection rules for passive and active users, guaranteeing the electrical power system stability and safety. Recently, the increasing diffusion of Distributed Generators from Renewable Energy Sources, mainly interfaced through electronic converters, has called for a drastic review of traditional approaches to distribution network operation. As a consequence, new regulating functions, aiming to support network stability by regulating local units power flows, have been defined, and others are under investigation. The paper discusses the role of existing and proposed stabilizing actions in terms of unintentional islanding identification, according to the Low Voltage interface protection characteristics.

INTRODUCTION

CENELEC TS 50549-1 [1] and 50549-2 [2] contain the recommendations for the connection of generating plants to the European distribution networks at Low Voltage (LV) and Medium Voltage (MV) respectively. Furthermore, standards CEI 0-16 [3] and CEI 0-21 [4] introduce the technical schemes and rules for the connection of passive and active users to the Italian MV and LV networks respectively. These documents consider also the simultaneous presence of both Distributed Generators (DGs) and Energy Storage Systems (ESSs) to make them compatible with present electrical networks.

Particularly, wider frequency and voltage operating ranges are allowed to avoid the untimely generating plants disconnection. In addition, MV and LV local units are required to participate in supporting the network stability: i) frequency regulation is sustained by modulating the DGs active power injection (*P/f* function); ii) reactive power control supports local voltage regulation along distribution feeders (*Q/V* function). Moreover, the paper discusses further regulating functions, such as Synthetic Inertia (SI) and Fast Voltage Support (FVS), which are under consideration for adoption.

P/f and *Q/V* regulations

In case of over-frequency transients, grid codes require a reduction of DGs active power injection, specifying a droop curve as the *P/f* characteristic in Figure 1 (left). The frequency measured at the inverter terminals define the converter operating point. Once the frequency derivative becomes negative, the static generator is called to maintain the power *p'* for a duration of 300 s, avoiding rapid frequency oscillations.

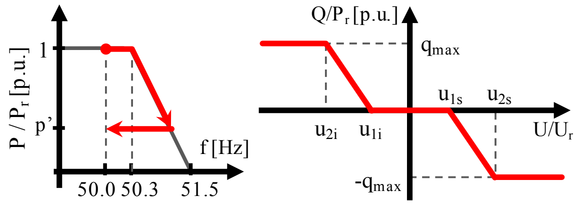

Figure 1. Active (left) and reactive (right) power regulation characteristics (*P/f* and *Q/V* respectively) in CEI 0-21.

The reactive power management guarantees DGs participation to local voltage support, referring to the *Q/V* characteristic, as the droop curve depicted in Figure 1 (right). As long as the measured voltage remains into a dead-band region close to the nominal value, the generator power factor is equal to 1. Conversely, provision of capacitive or an inductive power is required to the DG unit in case of under- or over-voltage conditions respectively. A time delay is generally not considered even if it could be instituted. Referring to Figure 1, this work considers: u_{2i}=0.90 p.u., u_{1i}=0.95 p.u., u_{1s}=1.05 p.u., u_{2s}=1.10 p.u. and q_{max}=0.4843 p.u.

Interface Protection System

The analysis of steady-state or slowly varying regimes confirms the benefits of the above mentioned stabilizing processes in terms of power quality. At the same time, the increasing risk of uncontrolled islanding on distribution networks represents an emerging issue. Several studies have been developed highlighting the effects grid codes requirements [5].

In particular, standard [4] defines the Interface Protection System (IPS) as a passive unintentional islanding protection which disconnects DGs and ESSs in case the measured frequency or voltage are out of defined thresholds.

The frequency protection operates with restrictive or

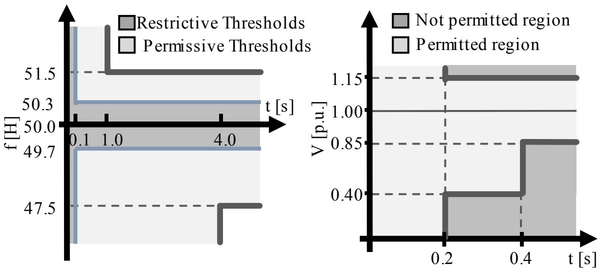

Figure 2. Frequency (left) and voltage (right) protection thresholds in CEI 0-21.

permissive thresholds, as depicted in Figure 2 (left). If the restrictive mode is activated (through an external signal), the protection disconnects the unit from the main grid in case the frequency is outside the range 49.7-51.3 Hz for more than 100 ms. Otherwise, the permissive thresholds of 47.5 and 51.5 Hz are applied, for 4 and 1 seconds respectively.

The under- and over-voltage protections implement the Fault Voltage Ride Through (FVRT) logic (Figure 2, right). Rapid voltage transients are allowed preventing the untimely ISP intervention and preserving the DG unit operation during faults.

FURTHER STABILIZING FUNCTIONS

The previously described regulating actions are presently required by the Italian standards, whereas other functions have been just proposed by European technical documents. The paper investigates the integration of SI and FVS in addition to *P/f* and *Q/V* regulations, focusing on fault contribution and islanding detection.

Voltage Support

In MV networks, generating units are called to modify their reactive behaviour in case of fast voltage perturbations. This stabilizing function, named Fast Voltage Support (FVS), is able to support the voltage stability [6]. In this work, FVS is introduced also for generating units connected to the LV network in order to evaluate its effect, in particular during faults.

The FVS logic (Figure 3) takes into account the fundamental voltage at both the positive and the negative sequence. In case a fast variation is observed, a reactive current injection in the positive and negative sequence respectively is required to the electronic converter, as indicated in (1) and (2). The voltage steps ΔU_1 and ΔU_2 are evaluated with respect to the previous minute average value.

$$\Delta I_{Q1} = k \cdot \Delta U_1 \quad (1)$$

$$\Delta I_{Q2} = k \cdot \Delta U_2 \quad (2)$$

A configurable dead band inhibits the FVS in case the measured voltage remains close to the nominal value. The management of the reactive power at both the positive and the negative sequence allows DGs and ESSs to control voltage amplitude and to balance phase voltages [7].

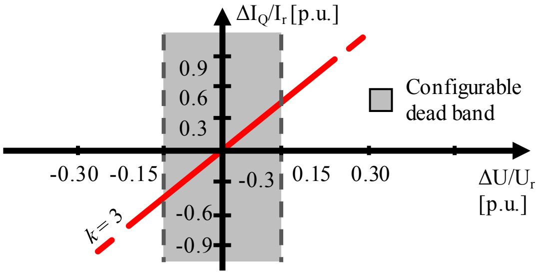

Figure 3. Fast Voltage Support [2].

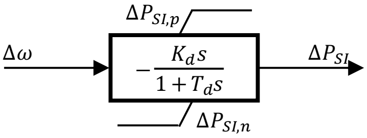

Figure 4. Synthetic Inertia control scheme.

Synthetic Inertia

In addition to the *P/f* action, SI is a further active power regulation usually applied in modern Wind Turbines (WTs), with appreciable benefits in terms of frequency stability [8]. Differently, in this paper, SI is applied to the static distributed generators (e.g. photovoltaic) connected to LV networks with the scope of investigating its effects on frequency oscillations and unintentional islanding identification.

Presently, DG units, even if the *P/f* function is required, do not modulate their injected active power to support network stability during fast frequency perturbations (as intrinsically done by rotating generators). To simulate the behaviour of traditional units, a control scheme performing the SI can be implemented in static generators. The SI forces the power converter to inject (or absorb) an additional active power which can be supplied by a reduced size storage system combined with the generator.

Figure 4 represents the most common model for SI representation [8]: the additional active power ΔP_{SI} is related to the time derivative of the frequency deviation $\Delta\omega$, while a low-pass filter avoids active power oscillations. The proportional constant K_d is related to the desired inertia constant H the device is required to have.

LV NETWORK CASE STUDY

In this work, a typical LV network has been schematically represented to evaluate voltage and frequency profiles over time (Figure 5). The case study refers to a simplified system, but the results can be directly applicable to real LV networks, even if larger and more detailed. Three main devices compose the LV system (rated voltage 0.4 kV): i) an equivalent load ("Load_01"); ii) a reactive compensator ("Capacitor Bank"); iii) a DC voltage source connected to the AC bus through a PWM Converter ("Static Generator"). Before the islanding formation, the LV network is connected to a MV equivalent grid ("External Grid", rated voltage 20

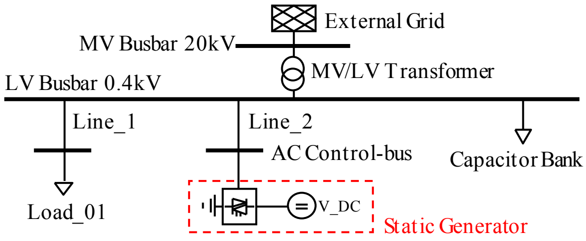

Figure 5. Simplified LV network.

kV) through a MV/LV distribution transformer (group Dyn11, S_n=400 kVA).

The compensator is directly connected to the transformer LV side in the secondary substation, while two three-phase dedicated lines connect the equivalent load and the generating group (LV lines, aluminium section of 185 mm^2 and length of 300 m).

The residential users distributed along the LV feeder are represented in aggregated form by "Load_01" (nominal active power Pn = 50 kW, effective absorption related to voltage and frequency at the connection node, power factor equal to 0.93).

DGs connected to the LV network are represented by the "Static Generator" (rated power 100 kW). The static converter control scheme is able to implement the above described regulating functions, such as *P/f*, *Q/V*, FVS and SI. The timely operation of the generator IPS has been tested considering different scenarios in terms of imbalance between generation and load, i.e. modifying the generator active power set-point.

Simulations have been carried out developing dedicated control models in DIgSILENT Power Factory software. Two network events have been considered in details to investigate the power regulation functions in a wide scope: i) unintentional islanding due to LV network separation from the MV/LV transformer; ii) short-circuit at the LV side of the transformer.

Frequency stability in islanding events

The opening of the switch downstream the transformer at the time instant t=1 s causes the islanding formation, so the LV network may remain energized by the local generator. Before the LV network separation, DG power factor is set to 1 and the capacitor bank is initially de-energized. The SI contribution is characterized with the proportional constant K_d =0.0064 [p.u.] (equivalent to H=1 [s]), the low-pass filter time constant T_d=0.5 s and the maximum inertia contributions $\Delta P_{SI,n}$= –10% and $\Delta P_{SI,p}$=10%.

Different values of the generator active power set-point ($P_{setpoint}$) have been examined (Table 1): i) $P_{setpoint}$ lower than the load consumption (75%); ii) $P_{setpoint}$ equal to the load consumption; iii) $P_{setpoint}$ higher than the load consumption (125%). For each case, three configurations have been considered: a) no power regulations (DG operates with fixed active and reactive power set points); b) activation of *P/f* and *Q/V*; c) synthetic inertia in addition to *P/f* and *Q/V*. Results are reported in Table 1, specifying whether the ISP correctly operates extinguishing the undesired islanded phenomenon in less than 5 seconds (✓) or not (×).

Table 1. Scenarios and results in case of islanding event

Generator $P_{setpoint}$	Scenario	*P/f* and *Q/V*	Synthetic Inertia	ISP correct action
37.5 kW 75% P_{load}	(i.a)	×	×	✓ (CB ×)
	(i.b)	✓	×	✓
	(i.c)	✓	✓	×
50 kW 100% P_{load}	(ii.a)	×	×	✓ (CB ×)
	(ii.b)	✓	×	×
	(ii.c)	✓	✓	×
62.5 kW 125% P_{load}	(iii.a)	×	×	✓
	(iii.b)	✓	×	×
	(iii.c)	✓	✓	×

The analysis of the results confirms that the unintentional islanding stable operation is generally fostered by the activation of regulating functions. In particular, in case an active power balance between load and generation exists (case ii), the LV portion of network reaches a stable operating condition after the islanding formation with the sole activation of *P/f* and *Q/V* regulations (presently required by the Italian standard). This means that no heavy frequency and voltage perturbation occur, so the loss-of-main protection is inhibited. Furthermore, if the capacitor bank compensates the reactive power imbalance between load and generation (sub-scenario "CB" in Table 1), the islanding operation is maintained also in case all the regulating functions are deactivated.

Differently, in case of active power deficit (case i), the role of SI is fundamental to guarantee a stable islanding operation for a not negligible duration. Figure 6 reports the simulation results for the scenario (i.c): active power, reactive power, voltage and frequency profiles during the transient are represented. For the power profiles, plain lines represent the inverter entities, meanwhile dotted lines the load ones. It is clear that the activation of the SI

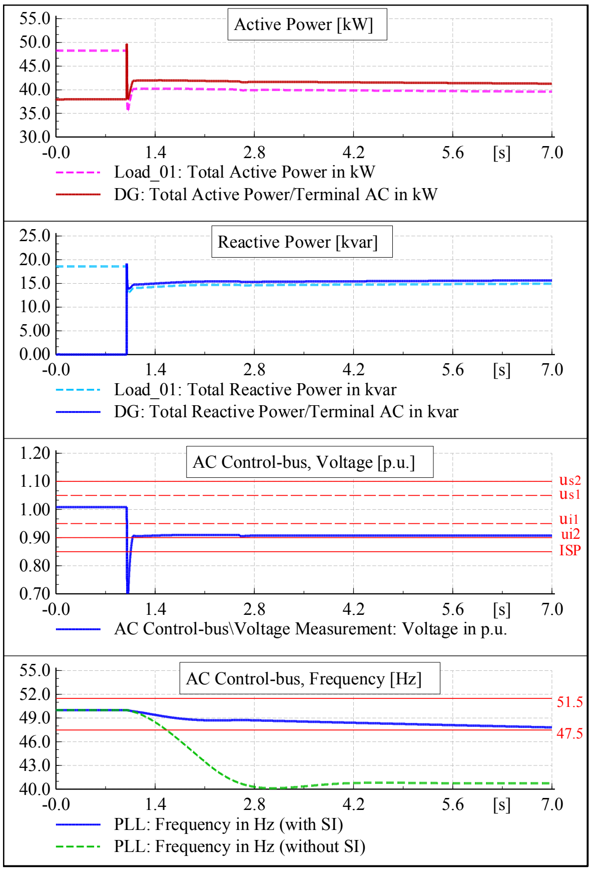

Figure 6. Active/reactive power, voltage and frequency profiles for the scenario (i.c).

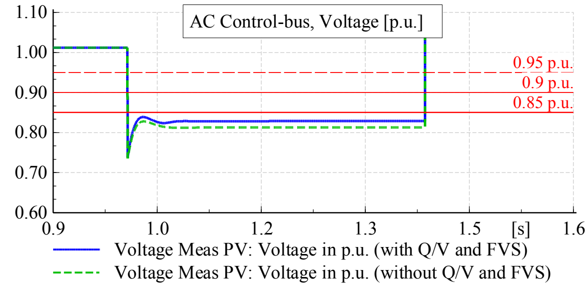

Figure 7. *Q/V* and FVS contribution during short circuit fault.

reduces the frequency perturbation and compromises the ISP effectiveness (blue plain frequency profile). Instead, without SI the ISP correctly operates (under-frequency relay, green dotted frequency profile).

In case of active power surplus, results are comparable with those of the scenario (ii): *P/f* and *Q/V* regulations are sufficient to inhibit the ISP action even if the inertia emulation is switched off, case (iii.b).

Voltage stability during faults

The contribution of FVS is analysed assuming a three-phase short circuit event at t =1 s at the MV side of the MV/LV transformer, considering a resistive short circuit impedance equal to 1.3 Ω. The fault involves in the entire network a symmetrical voltage drop. The system remains energized by both the DG unit and the equivalent MV source, which maintains the frequency almost constant up to the ISP action (0.4 s after the fault event due to under-voltage protection).

The DG active power set-point has no influence on the simulation results, since the MV grid compensates the generation-load imbalance. Two scenarios with different activated functions have been considered: a) no regulations; b) activation of *P/f*, *Q/V* and FVS. SI is not influential, due to the stability of the frequency.

The FVS function is implemented with the proportional parameter k equal to 3, similarly to the MV grid standard. A maximum current equal to 150% of the rated value defines the inverter capability constraint during transient phenomena (including both *Q/V* regulation and FVS).

Results reveal that, even if the ISP operation is always well-timed, the contribution of stabilizing functions during the fault is not negligible. In Figure 7, the voltage profile obtained in the 2 scenarios are superimposed. The voltage, close to the rated valued before the fault event, drops under 0.85 p.u. as consequence of the short circuit. The contributions of *Q/V* modulation and FVS support the voltage (blue line). Therefore, the detection of fault conditions, considering the measurement error, could result more critical due to the stabilizing functions contributions.

CONCLUSIONS

The ever growing DG diffusion is requiring the cooperation of dispersed units in supporting voltage and frequency stability. So, advanced regulating functions have been imposed to local static generators. Over-frequency perturbations are minimized by limiting the DGs active power injection, meanwhile the voltage stability is sustained through reactive power exchanges. In addition, further requirements are under study, such as FVS and SI.

The benefits of the stabilizing regulations applied to DGs are well known in case of steady state or slowly varying operating condition, but at the same time they could have detrimental effects in terms of fault protection and islanding detection.

Simulation results demonstrate that present grid code requirements are not able to exclude islanding. Significant parts of the LV grid could be energized by dispersed units for a not negligible duration after switching events in the main grid. Anomalous conditions could be not identifiable by ISPs due to the limited frequency/voltage perturbations during the island formation. Both the introduction of further stabilizing functions (voltage support and synthetic inertia) and the insertion of compensating units to regulate the end-user or the network power factor dramatically increase the risk of failure of present loss-of-main protections.

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