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Renewable power integration in Sicily: frequency stability issues and possible countermeasures

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Abstract

The exploitation of Renewable Energy Sources (RES) allows to reduce the electricity energy supplied by fossil fuelled power plants but introduces significant issues in power system planning and operation. Especially for small islanded systems, a larger share of load covered by RES, mainly wind and photovoltaic (PV) plants, implies lower inertia and reduced regulation resources to address frequency stability issues.
The paper focuses on frequency stability criticalities of the power system of Sicily operated as an electric island. Starting from the reconstruction of a real incident occurred in 2011, several scenarios are analyzed, characterized by different countermeasures (e.g. PV retrofitting, advanced controls on wind farms). The aim is to evaluate the benefit on security brought about by the introduction of these solutions. The study relies on the dynamic simulation of the control/defense/protection systems relevant for frequency stability.

Introduction

The growing penetration of Renewable Energy Sources (RES) allows to reduce the consumption share covered by fossil fuelled power plants, but it introduces several vulnerabilities in power systems operation [1]-[5].
Highly localized renewable generation may induce local grid congestions. At system level, however, especially for islanded systems, major challenges regard the regulation resources to address frequency stability issues. A larger share of load covered by renewables implies a reduction of the number of conventional units in operation. With the regulatory framework currently in force in most countries, RES plants provide no or limited contribution to inertia and frequency regulation. This implies lower system inertia and lower primary control reserve to counteract sudden power imbalances. Moreover, in many countries the thresholds for under/over frequency relays for distributed generation, and in particular for photovoltaic units connected to Medium/Low Voltage networks, are (or have been, up to recently) very stringent. In Italy, typical settings for under/over frequency relays were respectively 49.7 and 50.3 Hz for photovoltaic units commissioned before May 31, 2012: as a consequence, an underfrequency transient can cause the protections to intervene by shedding generators thus increasing the power unbalance in the grid [4].
These characteristics, combined with the increased requirements for tertiary reserve due to RES forecast errors, and for higher ramping rate of dispatchable generators in order to follow RES (and load) ramps, would call for the commitment of considerable dispatchable generation, also needed to support grid voltage. However, the commitment of a high number of conventional (thermal) units in islanded systems may be critical due to minimum power output constraints. In fact, RES have priority of dispatch (according to the current policies) and limited controllability (especially true for dispersed RES), hence keeping the power balance with high RES levels combined with the requirements of conventional generation in service, may become an issue. This situation, which can be particularly severe under light load conditions, calls for the adoption of additional control resources and/or new operational strategies.
The paper analyses frequency security issues in the Sicilian power grid, with focus on the short-term frequency transients associated to sudden power imbalances like those caused by the loss of generating units. Starting from the reconstruction of a real incident occurred in 2011, several scenarios are presented and discussed. These scenarios aim to evaluate the impact on security of modified control and protection systems of the current generation facilities, or the impact of new devices or operational strategies, in order to increase security.

Sicilian power system: an incident scenario

General features

The power system of Sicily is synchronously interconnected to the continental European power system via a single 380 kV, 1000 MVA AC link, but during the periods of (planned or unplanned) outage of this branch, Sicily is operated as an islanded system.
The monthly peak load has ranged from 2300 MW to 3700 MW for the last 10 years.

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At the end of 2011 the conventional generation capacity consisted of 5.8 GW of fossil-fuelled units (mainly steam and combined cycle gas turbines) and about 730 MW of hydro units (580 MW with hydro pump units). At the same date, RES included about 866 MW of PV installed power and 1680 MW of wind power. Also 54 MW of installed biomass power are considered. Thus, renewable sources play an important role to cover the island consumption and pose serious issues to operational security.

Incident scenario

On May 18, 2011, the Sicilian power system was operated in islanded conditions due to scheduled maintenance of the 380 kV interconnection line to the continent. The incident consisted in the tripping of an oil-fuelled unit at S. Filippo del Mela power station, causing a 150 MW power deficit. The resulting, fast frequency drop beneath 49.7 Hz caused the photovoltaic units to trip, thus provoking an additional 200 MW deficit. This in turn caused the frequency to drop under 49.0 Hz: at this frequency level the automatic load shedding scheme intervened by shedding about 180 MW of load, thus bringing back frequency to acceptable values. Fig. 1 shows the 220/400 kV power system in Sicily and the location of San Filippo del Mela Power Plant (PP).

Fig. 1. Sicily power system (220/400 kV levels) and the location of San Filippo del Mela power station

Power system model

Based on public information provided by the Italian TSO [7]-[8], a suitable dynamic equivalent model of the Sicilian system was set-up.

Load/generation profile for incident scenario

Initially, the total conventional capacity in service at the time of the incident was evaluated.

Based on TSO frequency transient measurement it is possible to estimate the “network power frequency characteristic” of primary control, i.e. the global response in megawatts per Hertz (MW/Hz) of the power system in terms of primary control. Given the steady state frequency value (49.75÷49.8 Hz) and the final power deficit (about 150 MW) resulting from load shedding intervention, the network power frequency characteristic is found to be about 600÷750 MW/Hz [9]. Considering an average 5% droop setting for all conventional units under primary frequency control yields to a total conventional installed power in service (after the loss of the thermal unit) of about 1500÷1875 MW. This estimation of the installed capacity in service must be checked against the load/generation balance and contingency reserve requirements. On the basis of TSO hourly demand forecast and day-ahead market session [10] the hourly load at 10 hour a.m. is assumed equal to 2250 MW. Given 260 MW of actual wind generation, the total RES (wind and solar) hourly production is about 460 MW. Thus, it is necessary to cover 1790 MW of load using conventional units. Moreover the TSO Grid Code requires at least ±10% of maximum net power output as minimum regulating band for primary frequency control. In order to determine the secondary reserve, one can refer to the “control capability for variations” method [11] proposed by European TSOs (according to which the minimum secondary reserve requirement is ±2÷3% of expected hourly load). The tertiary reserve includes fast responding reserve (i.e. 15 minute reserve) up to 1-hour reserve (replacement reserve). Based on reserve values published by the TSO for May 18, 2011 one can assume an upward regulating band of about 70 MW and 230 MW respectively for secondary and 15-minute reserves. Finally, the conventional capacity is estimated around 2300 MW including primary reserve margin.
Large chemical and petroleum process plants are located in Sicily. Thus, the large energy demand (heat and power) is supplied by fossil-fuelled power units (steam turbine, combined cycle and open cycle gas turbines, combined heat and power units) often located very close to industrial plants. Their power outputs are often set to fixed, high loading factors, due to energy demand or special energy production regime (i.e. units under CIP6 Act [12]).
Table 1 indicates the set of conventional thermal units modeled in the test system and supposed to be in operation during May 18, 2011 incident. The non-dispatchable fossil-fuelled units are considered under special CIP6 regime: their power generation is assumed at 90% of maximum net power output. The biomass injection is supplied by small power units so that the maximum power output is set to 50 MW without primary control.

Table 1. Set of thermal units in service in Sicily for the incident scenario of May 18, 2011 (GT=gas turbine; ST = steam turbine; CC = Combined Cycle; PP = Power Plant)

Power Plant ID	Technology	Rating [MW]	Dispatchable
PP1	CC	2x161 (GT)	No
		2x115 (ST)	
PP2	CC	1x260 (GT)	Yes
		1x130 (ST)	
PP3	CC	1x157 (GT)	No
PP4	CC	4x80 (GT)	Yes
		2x80 (ST)	
PP5	Steam Oil	2x320 (ST)	Yes

Dynamic models for control/defense/protection systems

As frequency stability is the major focus, and the system size is relatively small, a single bus approach was considered for the analyses.

The dynamic model of the system includes in particular:

- Conventional units, with prime mover and governor (different typologies are involved: oil-fired units, combined cycles, etc.)
- Under/overfrequency protection systems for distributed photovoltaic units
- Automatic load shedding schemes with different thresholds based on frequency and frequency derivative, according to the specifications from the TSO [13]. This defense scheme firstly acts on pumps (first thresholds at 49.8 and 49.5 Hz) and then on dispersed loads (first threshold at 49.1 Hz for continental grid)
- Inertia emulators for wind turbines (for the evaluation of possible future scenarios)

Standard IEEE models [14] are adopted to model the prime movers and governors of conventional units.

The under/overfrequency protection relays for PV units connected to LV/MV networks play an important role on frequency stability. In particular, due to their original very strict settings (49.7-50.3 Hz) in existing units installed before the application of new TSO requirements [15][16], an underfrequency transient could cause the protections to intervene by shedding generators thus contributing to power imbalance in the grid.

In order to mitigate the risk of DG tripping in case of system disturbances, especially in countries with large penetration of photovoltaic units in distribution networks, operation issues related with PV systems have recently been addressed by the European TSOs. The Italian TSO (TERNA) and the relevant Authority of Electricity and Gas (AEEG) have recently introduced new grid connection guidelines for DG power plants in March 2012. Under new grid code requirements, all PV units commissioned after March 31, 2012 must be endowed with under/over frequency relays with thresholds respectively equal to 47.5 Hz and 51.5 Hz. Moreover all new PV units in service after July 31, 2012 must reduce the power output in case of overfrequency, by a frequency-power droop characteristic. The PV units commissioned before March 31, 2012 with a power rating not smaller than 50 kWp connected to medium voltage networks must undergo a retrofitting process which sets the same thresholds for under/overfrequency relays as of new plants.

The automatic load shedding scheme is considered, aimed to shed pumps and dispersed loads in case of severe underfrequency conditions, according to the Italian defense plan [13]. The pump shedding scheme sheds all the pumps within frequencies not lower than 49.2 Hz and in the frequency derivative range of -0.2/-0.5 Hz/s. As far as dispersed loads are concerned, the first four shedding steps of the relevant shedding scheme are activated in case conditions like (1) for step *j* are fulfilled (based on frequency and rate of change of frequency), while the last four steps are activated in case conditions like (2) are identified (based on frequency only).

$$\left(f < f_{avv\_j} \quad AND \quad \frac{df}{dt} < df_{Thres\_j}\right) \quad OR \quad \left(f < f_{LIM\_j}\right) \tag{1}$$

$$f < f_{LIM\_j} \tag{2}$$

Basic settings for the automatic load shedding scheme related to dispersed loads are reported in Appendix A.

As far as wind farms are concerned, DFIG technology is considered (which accounts for the large majority of the wind turbines installed in Sicily). Detailed models of the aerodynamic part as well as of the power conditioning part are modeled. Details on the controls related to rotor side converter and grid side converter can be found in [17]. Besides an overfrequency control acting for frequency higher than 50.3 Hz, the wind farms can be equipped also with inertia emulation control in order to provide a fast power response to frequency deviations thus increasing global inertia of system [18]. Fig. 2 illustrates the models for the primary frequency control in case of overfrequencies and for the inertia emulation which modify the power set-point sent to the power controller of the rotor-side VSC converters of the wind turbines. In particular, the inertial response is given by $2H \cdot f \cdot {df}/{dt}$ where H is the synthetic inertia constant and *f* is the grid frequency. Proper filters (time constant T_{del})

are used to calculate d*f*/dt.

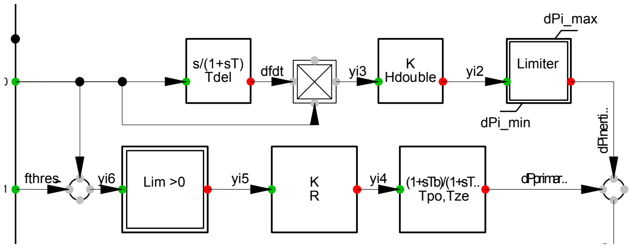

Fig. 2. Primary frequency control and inertia emulation models for WTs

Simulation case studies

Starting from the aforementioned base case, the effectiveness of some possible countermeasures is evaluated. To this purpose, several operating conditions are selected to evaluate the behaviour of the system as a function of some significant parameters:

- the level of deployment of retrofitting on frequency relays for photovoltaic units, in order to make the latter operate in the full range 47.5-51.5 Hz. Although the deadline for the retrofitting of all PV plants rated over 50 kW was March 31, 2013, in 2012 quite less than 30% of the installed PV power subjected to this new requirement had been retrofitted.
- the presence of pumped storage plants, which may be disconnected by the first steps of the automatic load shedding in case of power deficits
- the presence of battery energy storage, which may provide ultra-fast support to power imbalances
- the retrofitting of wind generators with advanced controls aimed to emulate the inertia of conventional synchronous machines.

The security criterion adopted for the analysis is the N-1, with the following performance requirement: the post-contingency frequency deviation must not be greater than 1.5 Hz in the transient period, and not greater than 0.5 Hz at the steady state of primary frequency control (i.e. within 30 seconds from the disturbance). This criterion is consistent with the requirements of the Italian grid code regarding frequency in islanded systems [19].

Base case: May 18, 2011 incident

Fig. 3 represents the simulated frequency transient caused by the aforementioned incident, according to the model herein presented.

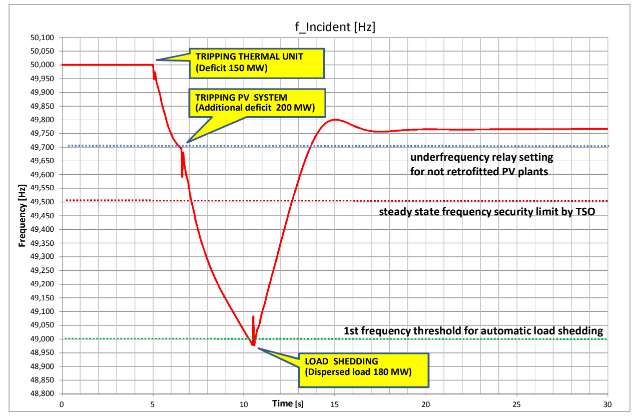

Fig. 3. Frequency transient of Sicilian incident reconstruction (18 May, 2011, 10:30 a.m.)

Results of the model closely match the time evolution of frequency provided by the Italian TSO TERNA [7][8].

Case 1: Retrofitting on frequency relays of PV units

The growth of PV installations in the Italian system mainly involves MV/LV networks with about 90% of the total PV installed capacity at the end of 2011.

About 360 MWp (42% of the total PV installed capacity at the end of 2011) were connected in Sicily during the incident of May 18, 2011. The thresholds of under/overfrequency relays were very strict (±300 mHz) according to the distribution grid code guidelines applied until March 31, 2012.

In order to evaluate the possible impact of the new grid code requirements concerning PV units on the security of the system during the recent incident in Sicily, three PV retrofitting levels are considered: 30% (current retrofitting situation), 50% e 100% of installed capacity.

Fig. 4 compares the frequency transient in case of the loss of the thermal unit injecting 150 MW, for the base case, and for three different PV retrofitting levels.

The first retrofitting level reduces the PV generation shedding to 160 MW, thus limiting the frequency transient above the first load shedding threshold (49.0 Hz). However the post-disturbance steady state frequency (49.46 Hz) is below the minimum acceptable steady state frequency according to TSO requirements (49.50 Hz). Thus, 30% of PV retrofitting is not sufficient to assure network security.

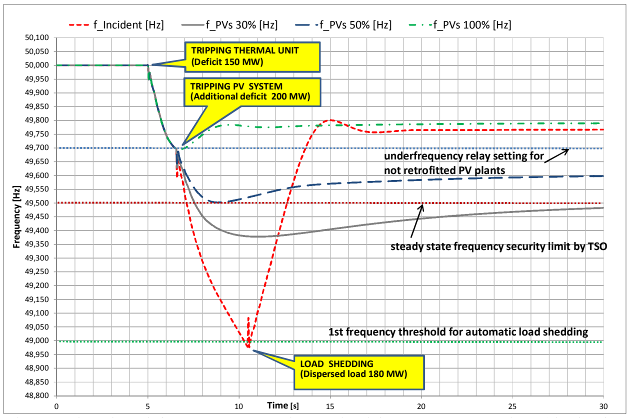

Fig. 4. Simulated frequency transients: incident reconstruction (dashed curve); 30% PV retrofitting (solid line); 50% PV retrofitting (long dash curve); 100% PV retrofitting (dot dashed curve)

In case of 50% PV retrofitting level, the PV generation loss is equal to 100 MW. The tripping of this amount of generation causes a post-disturbance steady state frequency (49.60 Hz) higher than 49.50 Hz. In this case frequency security is assured for the contingency under investigation.

If all PV units are retrofitted the total power imbalance is reduced to the loss of the thermal unit, and the post-disturbance steady state frequency is higher than 49.75 Hz.
It is worth noticing that 100% retrofitting level is only a theoretical limit: in fact, the new grid code requirements do not apply to small PV units with nominal power lower than 50 kW_p.

Case 2: Energy storage system

An energy storage system can increase the flexibility of operation and support the network stability requirements. Storage systems for renewable energy are given by pumping hydro power stations or special battery energy storage systems (BESS). These storage systems can provide energy services (energy delivery during low RES generation or high load demand) or ancillary services (e.g. energy provision in few seconds after a contingency in order to support the primary frequency control) [20], [21].
Two alternative energy storage systems are considered: existing pumping units in Sicily (Anapo and Guadalami hydro power plants) and new power intensive BESS devices in service during periods of high RES production.

In particular the first scenario assumes 50 MW of pumping units in service: this power amount is covered by additional conventional generation. The effect of pumping units is two-fold: (1) they increase total system inertia because they are synchronously connected to the grid; (2) they are subjected to the pumping shedding scheme which completely intervenes for frequencies higher than 49.2 Hz and for frequency derivatives in the range -0.2/-0.5 Hz/s.
Fig. 5 shows the frequency transient during May 18, 2011 incident in case of no pumping (dashed curve), with 50 MW pumping subjected to automatic shedding scheme (solid curve) and with a 50 MW BESS system (dot dashed curve). The first frequency threshold is set to 49.8 Hz. The tripping of 50 MW pumps reduces the power imbalance: the minimum frequency value is inside the range of insensibility (49.7-50.3 Hz) of under/overfrequency relays of existing PV units. No PV plants are lost, and dispersed load shedding is not required. Also post-disturbance steady state frequency fulfills security requirements by TSO.

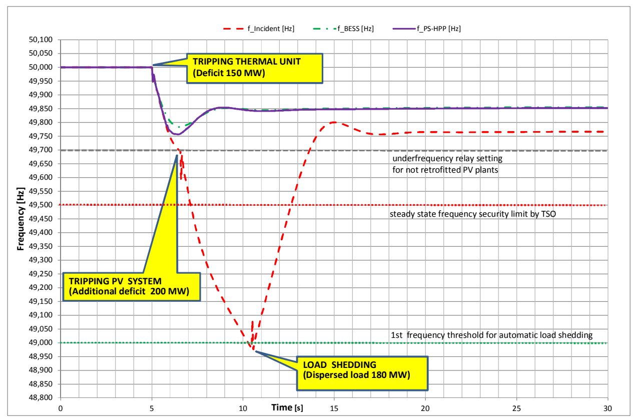

Fig. 5. Frequency simulation scenarios: incident reconstruction (dashed curve); 50 MW of pumped storage hydro unit (solid curve); 50 MW BESS (dot dash curve)

In case of BESS technology, a very fast response in terms of active power control is assumed for the battery system, taking into account the fast power control performances of AC/DC inverters and the state of charge limitation of battery devices. In particular it is required that the BESS injects the maximum power output in a time interval of 0.5-1 s after the contingency occurrence assuring a constant power injection for at least 15 minutes. The analyzed scenario considers a 50 MW battery with a 50 MWh rated capacity for frequency regulation applications [20][21]. The activation of BESS device reduces the imbalance by 50 MW so that frequency is kept above the thresholds of under/overfrequency relays for existing PV units without the loss of additional generation.
The fast BESS response allows to reduce the frequency largest excursion (frequency nadir) from 49.75 Hz (in case of 50 MW pumps) to 49.78 Hz.
The ROCOF (Rate of Change of Frequency) at 6 s moves from -0.165 Hz/s in case of no energy storage systems to -0.085 Hz/s and -0.045 Hz/s respectively with BESS and pumps.

Case 3: WTs advanced control - inertia emulators

The additional inertia emulator control is applied considering only the wind turbines commissioned after the application of Annex 17 from the TSO Grid Code [22]. In particular the inertia emulator is applied considering wind turbines with rated power of at least 2 MW or 0.85 MW corresponding respectively to 30% and 60% of all wind power installed power (1680 MW).
Fig. 6 compares the frequency transient during the incident in case of no inertia emulation (dashed curve) and for two penetration levels of inertia emulation: 30% of WTs with inertia emulation (only 2 MW rated machines are endowed with synthetic inertia, see dot dash curve), and 60% of WTs with inertia emulation (all machines rated ≥ 850 kW are endowed with synthetic inertia, see solid curve). Also a small penetration of inertia emulation (30%) prevents frequency from dropping below 49.7 Hz, by increasing the total system inertia in the early stages of frequency transient. This avoids the further loss of PV generation. Also the post-disturbance steady state fulfills security requirements (deviation lower than 500 mHz). A larger share of inertia emulation penetration (60%) reduces and delays the frequency largest excursion which moves from 49.71 Hz (at 7.1s) to 49.72 Hz (at 7.4 s). The ROCOF (Rate of Change of Frequency) at 6 s moves from -0.165 Hz/s in case of no inertia, to -0.150 Hz/s and -0.140 Hz/s respectively for a 30% and a 60% penetration of inertia emulation.

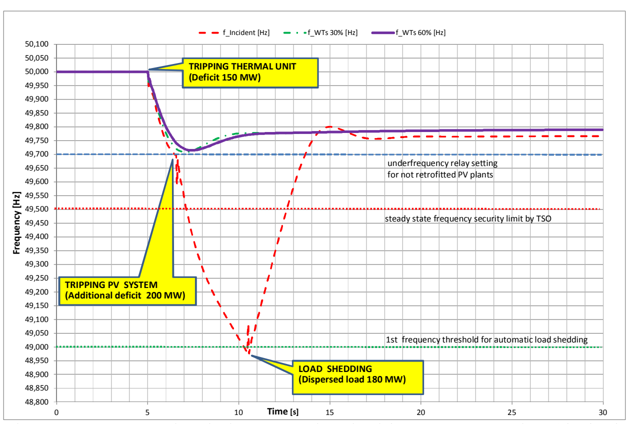

Fig. 6. Frequency simulation scenarios: incident reconstruction (dashed curve); scenario with inertial emulators on 60% of WTs (solid curve) and on 30% of Wts (dot dash curve)

It is worth also noticing that passing from 30% to 60% penetration of inertia emulation implies a slower frequency recovery after the frequency largest excursion: this is due to the fact that the larger inertia emulation effect the larger the power output drop experienced by the WTs after the inertial support provided in the very early stage of the disturbance transient.

Conclusions

The paper has presented the impact of different control systems, new devices, and operational strategies in order to enhance the frequency stability of an islanded system.
The analyses, including dynamic models of control/defense/protection systems, allowed to reconstruct an incident occurred in the Sicilian power system in 2011 and to show that the application of countermeasures (like PV retrofitting, storage and WF inertia emulation) would have prevented load shedding. A high PV retrofitting may be an effective countermeasures to reduce the impact of a further DG disconnection at 49.7 Hz. The introduction of advanced controls on WTs as well as the adoption of storage systems (either BESS or pumping storage subjected to an automatic shedding scheme) can help reduce the initial frequency drop thus avoiding that frequency decreases below the restrictive threshold of under frequency relays of not retrofitted PV plants.

Acknowledgment

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Appendix A

Table 2 shows the basic thresholds for the automatic shedding scheme for dispersed loads in the Sicilian power system.

Table 2. Basic thresholds for the automatic shedding scheme for dispersed loads in Sicily

Threshold nr	Activation frequency, f_{avv} [Hz]	Limit frequency derivative df_{Thres} [Hz/s]	Limit frequency, f_{LIM} [Hz]	Percentage of shed load, % of total load
1	49.1	-0.3	49.0	7
2	49.0	-0.6	48.9	7
3	48.9	-0.9	48.8	6
4	48.8	-1.2	48.7	6
5	-	-	48.6	6
6	-	-	48.4	6
7	-	-	48.2	6
8	-	-	48.1	5