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Assessment of the Dependence of Renewable Penetration Level in a Weakly Connected System on Available Control and Defence Systems

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ABSTRACT
The integration of non-dispatchable renewable energy sources (RES) poses serious challenges to power system planning and operation. At system level, a major issue regards the short and long-term frequency stability due to the reduction of regulating reserve margins, in turn brought about by the displacement of conventional generation and lack of contribution by the RES. This problem is especially present in isolated or weakly connected systems, and may become the limiting factor for renewable penetration.
The paper proposes a fast algorithm to quantify the benefits of advanced control, protection and defense systems in increasing RES penetration in weakly connected power systems. In fact, advanced solutions relying on both system design and operating measures may be of paramount importance to allow the secure integration of more RES generation. The algorithm is tested on a 2020 scenario of the Sardinian power system and it is cross-validated against time domain simulation.
Keywords: frequency, stability, power systems, control, defense, protection, wind power, photovoltaic generation

I. INTRODUCTION

The penetration of growing amounts of non-dispatchable Renewable Energy Sources (RES), mainly wind and solar (photovoltaic, PV), allows to reduce the consumption share covered by fossil-fuelled power plants [1]-[3], but introduces a number of criticalities in power system planning and operation [4]. In fact, RES are often located far from the bulk transmission system, therefore congestion and stability problems may arise. The network must be developed to connect renewable energy production and to access flexibility resources such as reserve capacity and remote storages. Very large excursions between minimum and maximum values of RES production call for the availability of conventional generation just to compensate for periods of low renewable production [5], [6]. Actually, conventional generation is more and more called to provide ancillary services rather than energy services, i.e. to compensate for RES and load variations rather than cover base load.

Significant issues are associated with frequency regulation. Renewable plants are usually operated with no upward margin in order not to “waste” the primary resource, thus they do not contribute to under frequency regulation. Moreover, the downward regulation required by grid codes is often less demanding than for conventional units. Because RES have priority of dispatch (e.g. in Europe), the “displacement” of conventional generation leads to a decrease in online reserve, unless more stringent constraints are imposed by the grid codes [7]-[12]. At the same time, forecast uncertainty of RES generation increases the reserve requirements from conventional units for balancing purposes.

RES and more in general Distributed Generation (DG) connected to the distribution level may cause local problems, such as power flow inversion possibly implying protection misoperation, unintended island, voltage deviations from nominal values, congestions. However, high penetration of DG may impact security at system level too. As far as system defense is concerned, the presence of DG may substantially affect the effectiveness of the load shedding schemes, which were designed when DG was negligible. Restoration process may be complicated by DG and in general by uncontrollable generation. In addition, the settings of under/over frequency relays of DG are, or have been until recently, very strict in many countries (e.g. ±300 mHz in Italy, +200 mHz in Germany): this may cause the tripping of distributed generation in case of system disturbances, especially in countries with large penetration of photovoltaic units in distribution networks, like Germany and Italy which have solved this issue by changing the connection requirements and carrying out retrofitting campaigns to modify the protection settings [13]. Operation issues related with PV systems have also been addressed by the European TSOs [14]-[17]. Frequency problems are of paramount importance for islanded or weakly interconnected power systems where larger frequency deviations are more likely to occur with respect to continent-scale power systems.

Different studies in literature tackle aspects of frequency stability assessment and control in weakly connected or isolated power systems: in [18] some issues related to frequency regulation and primary frequency control models in the Irish system are addressed. In [19] the ω-dω/dt plane is exploited to explore new under frequency load-shedding schemes (UFLS) for isolated power systems by identifying the frequency stability boundaries. In [20], [21] dynamic simulations are carried out to study the provision of dynamic frequency control support by energy storage systems [22] in an isolated system with large shares of RES. A still open issue consists into integrating evaluations of the impact of advanced control, protection and defense systems at a generation planning stage.

In this regard, the present paper aims to propose a method, based on frequency droop approach, aimed at fast evaluating the maximum RES penetration in power systems that are interconnected to the bulk power system via HVDC links or a single AC line, as may be the case of islands, accounting for the degree of deployment of advanced control, protection and defense systems, and with special focus on frequency stability which may be the most critical aspect for system security.

In particular, the investigation aims to show how the maximum allowable penetration of renewables depends (1) on the characteristics and degree of deployment of control, protection, and defense systems applied to RES, (2) on operational measures such as HVDC transit, and (3) on specific components such as batteries; and vice versa, which measures need to be set up to allow a certain RES penetration without jeopardizing security.

In the proposed approach, the maximum RES penetration is evaluated on most constraining, and rather infrequent situations. As a consequence, for many hours a year it may be possible to accommodate the production of a higher RES capacity. Only for limited periods of time RES generation will need to be curtailed, leading to wasted energy and increased system costs. Economic evaluations of the "optimal" RES capacity are out of the scope of this work. However, the proposed algorithm can be easily integrated into consolidated planning tools which can provide economic indicators over long time series, considering a wide range of possible scenarios.

The paper is organized as follows: Section II presents the methodology for fast assessment. Section III provides an outline of the model of a real weakly connected system, i.e. the Sardinian power system in a 2020 horizon. Section IV compares the results obtained by cross-validating the static approach with the time domain simulation of the most critical contingencies on a dynamic model of the system. An analysis of the impact of defense and control systems on penetration of renewables is reported in Section V. Final conclusions are given in Section VI.

II. METHODOLOGY FOR PRELIMINARY ASSESSMENT OF MAXIMUM RES PENETRATION

RES may impact on all security aspects, namely frequency, angle and voltage stability, and on overload. In order to identify critical features which may limit the penetration of RES in an isolated or weakly connected system, the following methodology has been elaborated.

2.1 Critical phenomena and contingencies

RES increase not adequately supported by network upgrading may create congestions, leading to overloads and possible cascading tripping with serious consequences for the system. Voltage control issues may arise too. However, here it is assumed that congestion can be solved through "normal" operational planning and network development. Similarly, local issues such as voltage support can be solved by measures that are relatively "easy" to implement (in terms of time, investment), e.g. the installation of compensation devices. On the contrary, when remote areas or islands are concerned, measures aimed to strengthen the interconnection to the main grid will be more costly and lengthy, and may not be viable in practice. This paper is therefore focused on the issues caused by weak interconnections.

Engineering experience suggests that the major criticalities in small and isolated or weakly connected systems, especially in case of significant RES generation, are related to the frequency dynamics resulting from sudden power imbalance. Accordingly, the most critical contingencies for frequency stability consist of the loss of power injections. In particular, as far as isolated systems are concerned, the under frequency caused by the loss of a generating unit is typically the most critical phenomenon. When weakly interconnected systems are concerned, the most severe contingency for frequency may be the loss of a connection to the bulk system, either an HVDC link or an AC line (in case of single AC interconnection; in case of several AC interconnection lines, other problems may arise such as angle stability). In particular, the loss of an exporting interconnection facility may cause an over frequency leading to the disconnection of generating units, in turn causing a power deficit and possibly blackout. This is more likely in scenarios characterized by high RES and low load.

2.2 Relevant situations

The maximum criticality for frequency is determined by the combination of a large disturbance and a low share of generators under power/frequency regulation. Accordingly, large RES injections and low load are critical factors. Two types of critical situations are identified:

1. nighttime situations with minimum load, maximum wind power production
2. daytime situations, characterized by high wind and PV production and load far from peak

The daytime case represents the most unfavorable situation in terms of load and non-dispatchable injections, assuming the simultaneous presence of a sunny hour and a high simultaneity factor for wind generation, in a spring holiday (i.e. when neither heating nor cooling are significant on system loading).

2.3 Security criterion

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 frequency requirements for weakly interconnected islands in the European grid code.

2.4 Regulation droop-based approach

The evaluation of maximum RES penetration according to frequency performance requirements can be preliminarily addressed with a "droop" approach, i.e. according to a simplified method that does not require a detailed model of the electrical network (single-busbar representation) [23]. Broadly speaking, the maximum RES production is related to the power export through the interconnections. The approach consists of identifying the export value through the most critical interconnector, which is associated to the limit condition in terms of frequency response in case of loss of the interconnector, given the available control resources and other system conditions. To this aim, transient and permanent droops of primary frequency regulation are used, as they relate the frequency deviation, the size of the disturbance, the capacity of the conventional generators in operation under primary frequency regulation (Frequency Containment Reserves, FCR), and the possible contribution to the regulation coming from DC links, neighbouring synchronous areas, and RES power plants (e.g. power modulation controls implemented in wind turbine and PV generators), according to the mentioned TSO Grid Code prescriptions [15]. The approach is briefly described by the following two steps [24].

In the first step, initial conditions of the power exported through non-critical HVDC and AC links are set (these are the links of smaller size with respect to the largest one). Assumptions on load, sun and wind allow to determine the base case RES injections. The parameters of the frequency control are then considered, namely of conventional generators, wind generators (if available, at least for downward regulation), and HVDC systems (for upward and downward regulation). These quantities, combined with the requirement of maximum admissible frequency deviation evaluated for the reference contingency (e.g. loss of one HVDC pole), allow to determine the minimum capacity (nominal power in MW) of conventional units in operation under primary regulation, which is needed to ensure the frequency stability of the network, as a function of the power exported through the critical interconnector. (It may be recalled that for a given disturbance, primary regulation contribution is proportional to the size of the regulating unit.) This minimum requirement for conventional power in operation allows to establish a specific configuration of conventional units to be assumed in service (unit commitment). These computations are based on the linearized formulas involving transient and permanent droop of the primary frequency regulation. In the resulting unit commitment, the minimum requirements of secondary and tertiary reserve must be met as well, otherwise more generators need to be committed.

Regarding the second step, the selected configuration of conventional dispatchable units is characterized by an overall minimum power, therefore it is necessary to verify the compatibility of the overall minimum power with respect to the power balance of the network. In this second step the amount of RES (wind and PV generation) injected into the grid can be determined by the following power balance expression:

$$P_{conventional\ gen} + P_{wind} + P_{photovoltaics} = P_{load} + P_{pumps} + \\ + P_{AC\ interconnectors} + P_{DC\ interconnectors} \tag{1}$$

where

$$P_{conventional\ gen} = P_{dispatchable\ conv.\ gen.} + P_{not\ dispatchable\ conv.\ gen.} \tag{2}$$

With obvious meanings of symbols; the left-hand side of (1) refers to the generation sources and the right-hand side to power absorptions (loads and exports). Thus, if one sets the values for loads, the greater the injected wind power, the smaller the injection of conventional power.

In particular, the maximum wind power injection is obtained by setting dispatchable conventional plants to their minimum power production. The greater the number of conventional plants in service, the greater the resulting overall minimum allowable production. Under this main assumption, in order to maximize the wind penetration one should operate as few as possible conventional units. On the other hand, the minimum power production for the conventional thermal units in service is given by security requirements. In case of the thermal units described in the test system the average minimum power is assumed as 40% of maximum net power output.

Moreover, in order to satisfy the minimum operating reserve requirements, the selected dispatchable units can be dispatched to minimum power output up to 60%. Therefore, in case of a high lower bound for the minimum allowable production, the maximum penetration of RES power can be significantly limited. The minimum operating reserve includes the Frequency Containment Reserve (FCR), Frequency Restoration Reserve (FRR), Replacement Reserve (RR), based on ENTSO-E Grid Code identification [25] and corresponding to the TSO Grid Code requirements as primary reserve, secondary reserve and tertiary reserve respectively [25][26].

III. TEST SYSTEM

The methodology is applied to an example of weakly connected power system, namely the Sardinian system at 2020 horizon. This power system has a peak load level of about 1000 MW during low load months and 2000 MW during high load months. The conventional generation capacity is composed by 3 GW of fossil-fuelled units and 460 MW of hydro units.

The installed wind capacity in the system is about 950 MW, of which about a large part (accounting for 400 installed MW) perform downward frequency regulation for frequency higher than 50.3 Hz. The capacity of biomass power plants is about 77 MW. The 400/220 kV grid is connected to the continent by two HVDC links: “SACOI” and “SAPEI” HVDC link. SACOI is a three-terminal HVDC link with Current Source Converter technology, monopole 200 kV DC, 300 MW, de-rated to 150 MW. The minimum power transmission is 30 MW. SAPEI is a bi-terminal HVDC link with Current Source Converter technology, bipolar ±500 kV DC, 2x500 MW. The minimum power level is 50 MW for each pole. Sardinia is also AC connected to Corsica via the “SARCO” 150 kV, 150 MVA submarine cable.

3.1 Scenario for 2020 horizon

A scenario analysis was performed by considering hourly load and generation profile for 2020 horizon: the main assumptions are reported in Table .

Table I. Data for 2020 scenario for sardinian power system

Quantity	Features			Notes
Load	Day peak	Night	Low daily load	Range: 1000-2000 MW
	1800 MW	1100 MW	1210 MW	
Biomass	60.3 MW bioliquid	63 MW solid	45.2 MW biogas	Total 77 MW (end 2011)
Thermodyn. solar	165 MW			
Hydro	220 MW (with 240 MW pumping)			
Conventional	3.46 GW			555 MW
Batteries	20 MW			No batteries in actual grid

The hourly load profile was allocated on local production capacity by profiling the hourly production on dispatchable and not dispatchable plants, with priority given to RES according to the current regulation, and taking into account the transit constraints on interconnections.

The analysis allowed to identify realistic situations as “worst cases” from the security viewpoint, according to the criteria described in Section 2.2. Two PV penetration scenarios (630 or 800 MW) are considered in 2020 horizon.

3.2 Reserve requirements

The TSO Grid Code requires that in Sardinia the required FCR must be supplied by all conventional units with a minimum contribution equal to ±10% of maximum net power output if the power unit rating is at least 10 MVA.

Moreover the permanent droop is set to the default value of 5%. The contribution of wind and PV units is limited to the power-frequency modulation in case of over frequency transients based on Annex 17 and 70 of TSO Grid Code. The FRR requirements is about ±2÷3% of hourly load (based on load variation control method proposed by ENTSO-E). The RR reserve is estimated in line with the guidelines provided by ENTSO-E [27]: it is calculated considering the average deviation of the generation and of hourly load forecast from actual value ($ADEV$), the standard deviations σ_L related to load forecast error and σ_G related to conventional unit output (to take into account possible unit outages) as described by (3) considering a 95% probability ($\alpha = 1.645$).

$$RR = ADEV + \alpha \cdot \sqrt{\sigma^2_G + \sigma^2_L} \qquad (3)$$

The maximum deviation takes into account the maximum generation unit loss. In case of Sardinian system the maximum net power for units is 200÷300 MW. In presence of wind and PV plants the above RR expression can be extended including the standard deviation for the forecast error associated to the wind and PV production under main hypothesis of standard Gaussian distribution. In particular in presence of very high RES production levels, about 5% and 2% of standard deviation (normalized on the relevant installed capacity) are assumed respectively for wind and solar productions, which is consistent with situations of high RES production. It is assumed that the most critical situation that must be compensated by the RR is the increase of hourly load or decrease of generation. In fact in case of load decrease or generation increase it is possible to use the power modulation control of RES.

3.3 Dynamic models

The dynamic models are developed in DigSILENT Power Factory to cross-validate the proposed planning tool. In particular, the models concern: *Control systems* (prime movers and governors of conventional units, primary frequency control applied to SAPEI HVDC link, over frequency control on wind farms, over frequency control on PV plants rated ≥ 50 kW, inertia emulators for wind turbines); *Protection systems* (under/over frequency protections for distributed PV units, over/under speed, over/under voltage protection for WTs), *Defense systems* (automatic load shedding schemes sensitive to frequency and its derivative, emergency tripping scheme for wind turbines in case of over frequencies); *Loads (*simulating the typical dynamic response of HV subtransmission networks in Italy*); BESS* (Battery Energy Storage system) based on Lithium-ion technology for grid frequency support.

During cross-validation, the following well-known indicators are used:

- Post-disturbance steady-state frequency (f_{ss})
- Largest frequency excursion ($f_{extreme}$)
- Rate Of Change Of Frequency (ROCOF)

IV. SIMULATION RESULTS

The above methodology was applied in two selected most critical scenarios: a) daily load with SACOI HVDC link in service and b) daily load without SACOI link.

Similarly the cross-validation with dynamic models regard the scenarios reported in **Table I**.

Table I. RES penetration scenarios for dynamic simulations

Scenario ID	Load Level	installed PV / WIND, MW	SACOI status	Focus
S1_1750	Daytime	630 / 1750	exporting 150	Impact of WT inertia emulation and of BESS
S1_1750_PV800	Daytime	800 / 1750	exporting 150	Benefits brought by pumped storage
S1_1900	Daytime	630 / 1900	exporting 150	Benefits brought by WT tripping scheme to allow larger RES penetration
S0_1475	Daytime	630 / 1475	Out of service	lack of exporting capability

4.1 Scenario 1 – Daily load with SACOI in service

In this scenario the daytime load of 1200 MW is considered and the HVDC links are both in service. SACOI is exporting its maximum power. The analysis of wind penetration is proposed, taking the export on SAPEI link as a parameter, i.e. the loss of one pole of the SAPEI HVDC link is the critical contingency.

The minimum required RR and FRR reserve is evaluated as 200 MW; the corresponding conventional units in service is about 680 MW working at 55% of maximum net power output. Considering also the must-run thermal units from biomass and solar thermodynamic technologies forced at 90% of their maximum net power and 630 MW of PV (without frequency disconnection thresholds), the droop-based methodology allows to determine the maximum wind power at minimum conventional units in service. Fig. 1 shows the maximum wind penetration assuming 60% of WTs subjected to over frequency control (without additional remote defense schemes) and an average simultaneity factor of 70% (i.e. wind production is 70% of the cumulated nominal installed wind power in the island). It is possible to install up to 1750 MW nominal installed wind power taking in service 1000 MW of conventional units (680 MW of dispatchable units and 335 MW of must-run generators) and 50 MW SAPEI margin. This maximum penetration level can be achieved with a margin on SAPEI equal to 50 MW per pole (assuming symmetric operation of the two poles), i.e. with SAPEI exporting 2 x 450 MW. This result is to be interpreted in this way: up to a certain extent, an increasing margin on SAPEI (with respect to the export at maximum level) allows a higher RES production, as it implies a smaller perturbation (loss of SAPEI pole) and a post-contingency higher contribution of primary frequency regulation from the safe pole of SAPEI (in the hypothesis of pre-fault symmetric operation). However, this trend stops at a certain point due to the presence of non-dispatchable conventional units and to the need to keep generators in service to provide reserve (FRR, RR).

The dispatchable units used to guarantee the operating reserve can be selected among thermal units (available rated powers 320/160/88 MW). In this case one possible combination is 2×320 MW fossil-fuelled units.

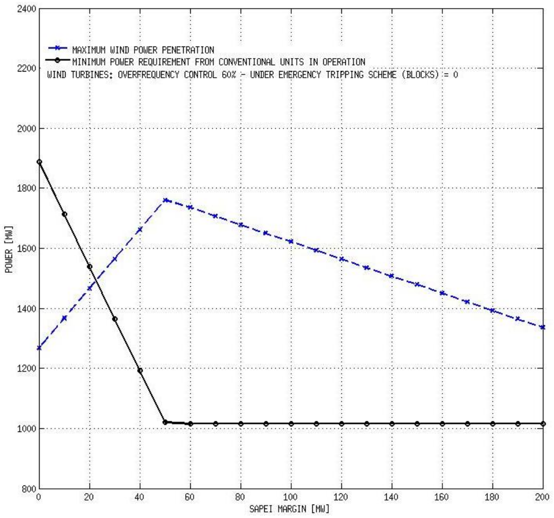

Fig. 1. Maximum wind power penetration and minimum nominal power of conventional units required in operation, daily load + two HVDC links in service

Fig. 2 shows the time evolution of frequency in case of the contingency in scenario S1_1750 for the "worst case" and for different PV retrofitting levels. Retrofitted PV plants remain connected to the grid in the whole frequency range 47.5-51.5 Hz, while non-retrofitted ones disconnect as soon as the frequency exceeds the range 49.7-50.3 Hz.

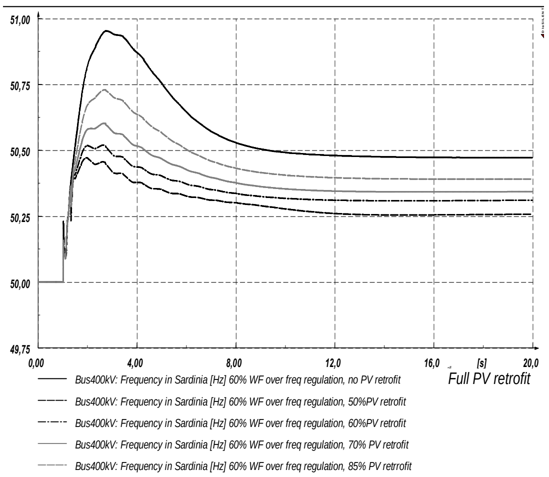

Fig. 2. Grid frequency in case of CTG 1 (loss of one SAPEI pole) for the "worst case" (100% PV retrofitting and load modelled as PQ constant load) and for more realistic scenarios of PV retrofitting (50, 60, 70, and 85%)

The solid curve in Fig. 2 confirms the outcome of the methodology aimed at assessing the maximum ("worst case") wind power penetration. In fact the contingency determines a steady state frequency deviation (480 mHz) very close to the security limit in the Grid Code (500 mHz). The slight differences are due to discretization issues present in the more detailed dynamic simulation (e.g. the choice of specific conventional units implies a total conventional power in service which is close to but does not coincide with the one coming from the static methodology).

In order to prove the correctness of the proposed approach in evaluating the maximum installed wind power, the cross-validation process analyses the S1_1900 scenario which considers an increment in installed wind power in Sardinia (1900 MW). The same production coefficient is adopted for the wind farms (70%). The additional wind power production is compensated by an increase in SAPEI export (passing from 450 MW to 500 MW per pole). Also in this scenario 60% of WTs (around 1200 MW of installed wind power) are endowed with over frequency control.

The dynamic simulation (as well as the static methodology) assumes a steady state overloading capacity of 110% for SAPEI link, thus an additional 50 MW upward reserve is assumed on each pole. The initial conventional unit production is unchanged. Fig. 3 shows the frequency in case of 100% PV retrofitting (worst case for over frequencies) and for more realistic cases with different PV retrofitting levels. The steady state frequency deviation (520 mHz) in the worst case violates the security criteria, in line with the outcomes of the static methodology.

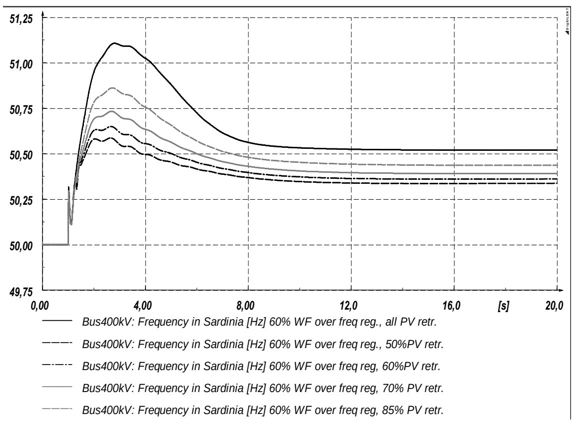

Fig. 3. Grid frequency for CTG 1 for the worst case (all PV retrofitting) and for realistic scenarios of PV retrofitting

A significant contribution to frequency regulation comes from wind turbines which undergo a power reduction ranging from 65 MW (in case of 50% PV retrofitting) to 158 MW (85% PV retrofitting). The largest frequency deviation ranges from 50.87 Hz (85% PV retrofitting) to 50.60 Hz (50% PV retrofitting). The steady state frequency deviation for 85% PV retrofitting (440 mHz) is still close to the security limit and further disturbances can cause security violations. Thus, in the present case a wind turbine tripping scheme must be adopted to accommodate the additional wind power installed. Fig. 4 compares the frequency transient in case of 85% PV retrofitting with (solid line) and without the emergency tripping scheme with two different values for tripping threshold, 50.3 Hz and 50.6 Hz respectively for the dashed and dot-dash line.

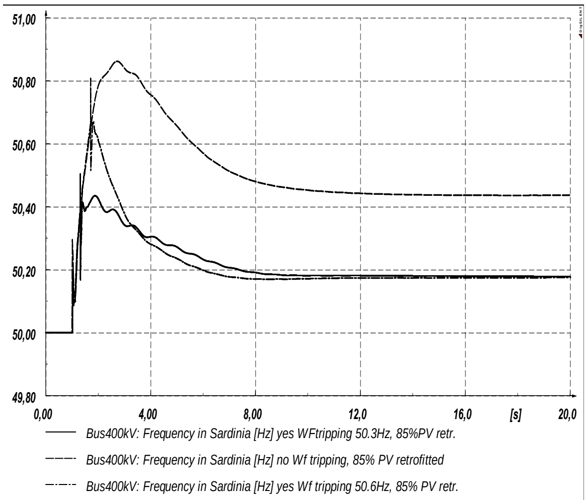

Fig. 4. Grid frequency for 85% PV retrofitting with (solid line) and without (dashed and dot dash lines) tripping scheme for WTs

At 50.3 Hz the emergency scheme trips 20% of WTs, thus curtailing around 260 MW generation. The largest frequency deviation is 50.44 Hz for the 50.3 Hz threshold and 50.67 Hz for the 50.6 Hz threshold, and the steady state frequency deviation is equal to 180 mHz for both settings (below the threshold to activate the over frequency control of WTs).

4.2 Scenario 2 – Daily load without the SACOI link

The Grid Development Plan of the Italian TSO takes into account the new SACOI project in order to replace the existing very old SACOI. This scenario assumes that at horizon 2020 the existing SACOI will be almost out of service under the main hypothesis that the new link will be under construction. Thus, the scenario excludes the 150 MW export contribution of SACOI link; the exporting capacity via DC links is reduced to 2×500 MW due to SAPEI link. Given the same load level, reserve requirements and must-run injections, 630 MW of PV installed power imply the possibility to install up to 1474 MW of wind power (see Fig. 5), considering a 70 MW margin on each SAPEI pole.

The dynamic simulations are performed on the specific operating point S0_1475 corresponding to the peak of the maximum allowable wind power penetration.

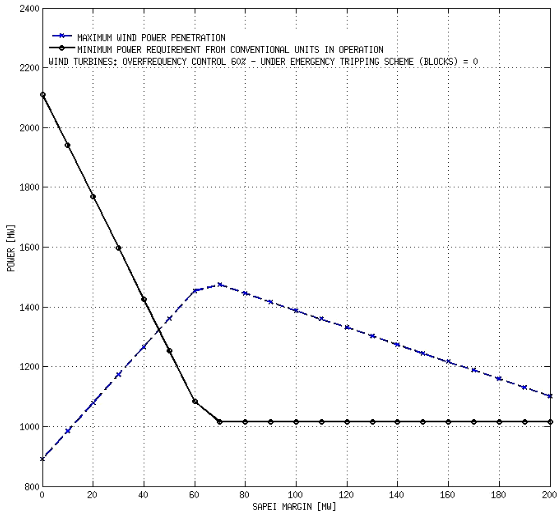

Fig. 5. Maximum wind power penetration, minimum required conventional power in operation, in case of daily load and only one HVDC link in service

The steady state frequency after the application of CTG1 is 50.460 Hz which is close to the limit imposed by the Grid Code (50.500 Hz): this confirms the effectiveness of the methodology in identifying the limiting conditions in terms of maximum allowable wind power penetration.

V. IMPACT OF CONTROL SYSTEMS ON MAXIMUM RENEWABLE PENETRATION LEVEL

Table II reports the results on wind power penetration cases for daytime and nighttime load scenarios in presence of over frequency control on WTs, assuming a total PV installed power equal to 630 MW. Simulations show that a 20% increment in the share of WTs subject to over frequency control causes the wind power penetration to pass from 1650 (see Fig. 1, in particular the y-value of the wind power penetration curve for a SAPEI margin of 20 MW×2) to 1850 MW, given the same margin on SAPEI HVDC link (20 MW×2) and the SACOI link in service. Similar benefits can be found in the nighttime load scenarios.

Table II. Wind power penetration cases with daytime and nighttime scenarios, in presence of over frequency control on a percentage of WTs, and different status (ON/OFF) of SACOI, 630 MW installed PV

Load scenario	% of WTs with over freq. control	Margin on each SAPEI pole, MW	SACOI status	Maximum wind power to be installed, MW	Minimum amount of power from dispatch able conv. units, MW
daytime	80	20	ON	1850	680
daytime	80	40	OFF	1560	680
nighttime	60	20	ON	2674	680
nighttime	60	40	OFF	2400	680

In case of a higher PV installed power (800 MW in S1_1750_PV800 scenario) the additional production from PV can be compensated using available pumped storage which helps accommodate a higher amount of wind power as Table III shows.

Table III. Wind power penetration cases with daytime scenarios, in presence of pumping storage and over frequency control on a share of WTs, different status (ON/OFF) of SACOI - 800 MW installed PV

Load scenario	% of WTs with over freq. control	Margin on each SAPEI pole, MW	SACOI status	Maximum wind power to be installed, MW	Minimum amount of power from dispatch able conv. units, MW
daytime	60	60	ON	1563	680
daytime	60	80	OFF	1275	680
daytime with pumps	60	60	ON	1823	680
daytime with pumps	60	80	OFF	1752	680

To cross-validate these results, the dynamic simulation focuses on S1_1750_PV800 scenario.

This scenario assumes a daytime load with SACOI exporting 150 MW and 1750 MW installed wind power, and a larger PV penetration is considered (800 MW instead of 630 MW of the base case S1_1750). Two possible ways to compensate the additional power output from PVs are analysed: (1) the additional PV production is exported by SAPEI poles which have to operate at 500 MW. The 10% overloading capacity is exploited for frequency regulation; (2) the additional PV production is stored in a pumping plant (Taloro) with maximum pumping capability of 240 MW.

Table IV summarises the post-disturbance steady-state frequency, the largest frequency excursion and the initial ROCOF found for CTG1 (loss of one SAPEI pole) for the two alternatives, with reference to the over frequency "worst case".

Table IV. largest frequency excursion, initial ROCOF, post-disturbance steady-state frequency for CTG 1 in the worst case without / with pumps in service

Scenario (800 MW PV installed)	Largest frequency excursion $f_{extreme}$, Hz	Initial ROCOF [Hz/s]	Steady state post disturbance frequency f_{ss}, Hz
no pumps	51.18	+1.43	50.54
pumps in service	50.92	+1.02	50.47

The first method does not allow to fulfill security constraint (f_{ss} is higher than 50.5 Hz). This confirms the outcome of the static methodology which estimates about up to 1560 MW as maximum wind power to be installed (with a 50 MW margin on SAPEI poles) in case of 800 MW of installed PV plants. The use of storage allows to increase the margin on the SAPEI pole (thus, reducing the power mismatch if one pole is lost) and it grants a higher regulating margin on the safe pole.

VI. CONCLUSION

This paper has proposed a fast approach to evaluate the maximum RES installed power on a weakly connected power system, and to assess the benefits of advanced control, defense and protection systems to increase RES penetration. The relevant algorithm can be efficiently integrated in generation planning tools aimed to evaluate the opportunity (over a long term) of increasing the maximum renewable penetration in weakly connected power systems.

The algorithm has been cross-validated on a 2020 model of the Sardinian power system by using a time domain simulator which runs the most critical contingency over several scenarios: the matching of results from the two approaches is good.

The adoption of an "ad hoc" wind tripping scheme which trips WTs in case of over frequency transients can allow larger amounts of wind power to be installed in the grid.

Further work may consist in exploiting the proposed algorithm to quantify the effect of the advanced control/defense systems on long term reliability indicators.

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