Stability analysis of the OSMOSE scenarios: main findings, problems, and solutions adopted

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***Abstract* — This paper presents the main findings, problems encountered, and solutions regarding the dynamic stability of future network operation scenarios in the presence of a high amount of clean, converter-based energy sources (renewables, storage, etc.) as studied within the OSMOSE European project. This study has been carried out on a portion of the Italian transmission grid where the most recent and innovative flexibility services have been implemented to preserve the dynamic stability for the scenarios selected. The most typical and critical generation/demand conditions have been recreated on the Sicilian grid for 2030 and checked. This research proves that in the future, different services, like synthetic inertia from renewable energy sources, flexible demand response, or reactive power provision from static converters, must be taken into account to preserve system stability as traditional generators are progressively phased out.**

Keywords—OSMOSE project, stability analysis, large perturbation angle stability, small perturbation angle stability, voltage stability, Italian network, synthetic inertia, demand response, reactive compensation.

I. INTRODUCTION AND MOTIVATION

This paper presents the results of the Deliverable concerning Stability Aspects, within the scope of the work performed by ENSiEL under Task 1.4.3, of the European project OSMOSE. The OSMOSE project and, in particular, the work package 1 [1], focuses on the Optimal Mix of Flexibilities, and started with Task 1.1 by proposing long-term future scenarios for both 2030 and 2050, which differ on demand levels, installed capacities, investment opportunities, and the amount of flexibility options. Next, within Task 2.2, static reserve adequacy analysis has been carried out by RTE, the French Transmission System Operator (TSO), using its ANTARES model, aiming to assess and validate these scenarios [2].

Utilizing the data generated from Task 1.1 and Task 1.2 as input, ENSiEL has evaluated the impact of innovative flexibility sources (e.g., Renewable Energy Sources (RES), battery energy storage systems, and demand-side response) on power system stability, testing them for 2030 in a realistic model of the Italian electrical network, provided by Terna, the Italian TSO. In particular, ENSiEL has assessed some typical perturbations of power systems, e.g., loss of a large generator or slow increase of loads, contingencies of branches, among others, by developing and implementing suitable models of power system components and controls in DIgSILENT PowerFactory 2019.

The following topics have been investigated:

- *Large-perturbation angle stability*: to determine the generator's response to the changes in frequency and voltage in a time scale from tens milliseconds up to 4/5 seconds, where electromechanical stability can be evaluated. This analysis considers both generators and loads dynamics. The goal is to evaluate if the synchronous machines can be kept in synchronism after a severe transient disturbance [3]: a fault, a change in the transmission topology, or a disconnection of a large generating unit.
- *Frequency stability*: to check the ability of the power system to maintain steady frequency following a severe system power unbalance between generation and loads. It depends on the system’s capacity to maintain/restore equilibrium between generation and load, with the minimum unintentional loss of loads [4] and/or disconnection of interconnection lines.
- *Small-perturbation angle stability*: to evaluate the dynamic of the generators in response to a small variation in loads and generation that occurs continuously on the power systems and not necessarily related to a transient disturbance.
- *Voltage stability*: to estimate the voltage variation during a slow increase of loads. Voltage stability is defined as the ability of a power system to maintain a steady acceptable voltage at all busses in the system under normal conditions and after being subject to disturbances. The main cause of voltage instability is the inability of the power system to provide enough reactive support [3].

II. DESCRIPTION OF SCENARIOS AND GRID USED

The grid model employed for this analysis is a portion of the Italian transmission network corresponding to Sicily (Fig. 1); basic data have been provided by Terna. Sicily presents few lines with a voltage higher or equal to 220 kV, and, considering the geographic dimension and the high amount of capacity installed, its network is poorly meshed. Since 2016, Sicily is connected to the Italian system through two AC interconnections at 400 kV, both starting from Rizziconi substation in the mainland and getting to the Sorgente substation on the Island. In particular, the interconnection activated in 2016 is composed of two parallel AC undersea cables. The 400 kV system essentially consists of a single backbone starting from the mentioned links in the extreme

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North-East and ending in the Syracuse petrochemical nucleus in the south-eastern part of the region; it goes through the powerful interconnection substations of Sorgente, Paternò and Chiaramonte Gulfi up to the ISAB plants near Priolo Gargallo. The primary transmission system is made by a big 230 kV ring, extended along with the coastal territories with a double circuit.

Fig. 1. The Sicilian grid [5].

The grid model is very detailed and presents:

- more than 600 busbars at 400, 230, 150 and 132 kV;
- 441 lines;
- 516 substations;
- 30 large (A_n>10 MW) static generators, representing the wind and solar plants connected to the HV grid;
- 379 loads, mimic both equivalents and HV loads;
- 72 synchronous machines, representing both thermal and hydro plants with their associated controllers (AVR, GOV and PSS).

Usually, during normal operation, Sicily exports to Italy a large amount of active power. This is done with the purpose of keeping the Sicilian power system in operation in case of the trip of the interconnection, thus avoiding load shedding on the Island. Generation surplus should be controlled by the primary regulation. However, active power transit is always monitored on the link, and if the exported power is higher than a certain amount, specific devices can disconnect some Sicilian generation.

Moreover, the Rizziconi – Sorgente Islanding relay trips when severe under frequency event occurs in the continental power system, trying to save the Sicily power system by disconnecting it from the mainland. The tripping relay operates according to these rules [6]:

- starting frequency of 49.7 Hz and frequency derivative lower than -0.2 Hz/s;
- frequency lower than 49.5 Hz.

In case of under-frequency events, a Load Shedding (LS) scheme is in operation, and its settings are shortly described in Table I; according to different thresholds, a load shedding step can be activated, as described.

TABLE I. LOAD SHEDDING SETTINGS [6].

Threshold	Starting frequency [Hz]	Frequency derivative threshold [Hz/s]	Pure frequency threshold [Hz]	Percentage of shed load
1	49.3	-0.3	49.0	9%
2	49.2	-0.6	48.9	8%
3	49.1	-0.9	48.8	7%
4	49.1	-1.2	48.7	7%

The Sicilian grid, identified in this project by the market zone 56IT by T.1.1 [1] and T.1.2 [2], has been updated with the new values of capacities and loads given by Task 1.1, area by area, for 2030. For this analysis, only the scenario "*Current Goal Achievement*" and its capacities have been implemented in terms of generators and loads profiles.

The following most typical and critical generation/demand conditions have been taken under consideration for stability analysis:

- very low load/very low rotating generation;
- high load/low rotating generation;
- maximum export/import of Sicily;
- weak network operating conditions (lines out of service);
- islanding conditions.

These snapshots have been selected considering the load demand, the generation technology mix, and the generation balance between the traditional generation and the renewable one to study the most critical and weak grid conditions.

Then, the time series profiles provided by Task 1.2 have been carefully analyzed, and the most appropriated hours, considered to better resemble the situations described above, have been picked up. Finally, 60% of the hourly demand provided has been assigned to the loads directly connected to the HV grid, while the remaining 40% to the loads connected to the distribution grids. The active power set points of the HV loads have been adjusted using a suitable scaling factor to increase, or decrease, the total demand and meet the required levels. The newly installed capacities have been allocated to the HV and MV grids, according to the current shares given by Terna and available on the GAUDI portal, the Terna's website with the technical characteristics of all plants connected to the Italian transmission system [7]. The selected Dispatching Profiles (DPs) are shown in Table II.

TABLE II. SELECTED DISPATCHING PROFILES (DPS) FOR 2030.

Dispatching profiles	Snapshot
High Import: quite high load and low local generation	9th April MCY 1 at 19:00
High Export: high RES and traditional generation production and low load request	22nd March MCY 4 at 08:00
High load: high load request satisfied by local mainly RES generation	19th June MCY 1 at 09:00
Low load: low load and low local generation	21st August MCY 1 at 02:00
Island: quite high load – Sicily disconnected from the mainland	19th June MCY 1 at 09:00
Grid in maintenance: low load and low generation – some 220 kV lines are out of service	21st August MCY 1 at 02:00

III. LARGE PERTURBATION STABILITY ANALYSIS: METHODOLOGY AND RESULTS

The large perturbation stability analysis has been realized through dynamical simulations in a time scale from tens of milliseconds up to tens of seconds, where electromechanical stability can be evaluated, considering generator and load dynamics and the triggering of protection schemes.

The six DPs of Table II have been considered, and, in each of them, a set of events have been simulated. Specifically, since Sicily is (and will be) connected with continental Italy through three AC cables, the outage of one and two of these connections has been simulated (except for the **Island** DP). Moreover, the outage of groups of large generating units has been considered.

According to the Italian grid code [8], frequency should be kept within the range 49.9 Hz – 50.1 Hz in normal operating conditions. For the special case of Sicily, when it is disconnected from the Italian peninsula, the normal condition range is assumed to be 49.5 Hz – 50.5 Hz. In emergency operating conditions, frequency should remain in the range 47.5 Hz – 51.5 Hz. According to [9], if frequency exceeds the emergency condition range of 47.5 Hz or 51.5 Hz, a system blackout can hardly be avoided. Therefore, in a given simulation, stability has been considered as guaranteed if the numerical integration has converged and frequency has been kept within the range 47.5 Hz – 51.5 Hz. Moreover, a simulation has been labelled as: *strongly stable,* if stability has been guaranteed and frequency has remained within the normal operating condition limits; *stable,* if stability has been guaranteed, but the normal operating conditions were violated; *unstable*, if stability has not been guaranteed.

In the 2030 forecasted scenario, according to results provided in Task 1.1, there are no Demand Side Response (DSR) services provided by loads and no battery storage systems. Therefore, two main network configurations were considered for each event for comparison: the "*base configuration*", where the Synthetic Inertia (SI) provided by wind generators is disabled and the "*RES configuration*", which is the configuration designed according to the provided forecasts.

Further network configurations with DSR ("*DSR configuration*") were simulated (again, even though it was not assumed in operation according to Task 1.1), to check if this flexibility option is useful in that framework to solve any possible unfeasibility showing up and to avoid LS. With this aim, a set of 24 DSR models for Fast Frequency Regulation (FFR) services, described in [10] have been added to the grid model. Briefly, the i-th load varies its active power import proportionally to the frequency deviation outside from a dead-band of ± 0.02 Hz, delivering the full reserve equal to $K_{DSR,i}$ [MW] at 0.2 Hz, that can be expressed in function of the percentage value p [%] (assumed equal for all involved loads) as follows:

$$K_{DSR,i} = \frac{p}{100} \cdot P_{L,i} \tag{1}$$

where $P_{L,i}$ [MW] is the operating point of the load. SI is provided as well. In this case, the power variation is proportional to the frequency derivative multiplied by a gain equal to the same $K_{DSR,i}$. Consequently, additional network configurations referred to as DSR-p have been realized, given the value of the percentage p.

Table III summarizes the results: in all the cases where the connection with continental Italy is kept, even if with one or two of the three cables, stability is guaranteed. This occurs both with and without the SI provided by wind generators. SI allows the maximal frequency deviation and the maximal frequency derivative to be reduced. Even if such effect results to be relatively small when the connection with continental Italy is in service, as the overall system inertia is huge, if compared with the portion provided only by the wind generators installed in Sicily, its provision is valuable as also shown in the next section.

In the **Island** DP, the loss of the inertia and of the primary regulation coming from continental Italy makes the frequency less stable. With one of the two simulated generation loss events, frequency exits from the normal operating conditions, and stability can only be guaranteed by LS. Fig. 2 shows the detailed results of this case. It can be observed that the support of DSR can avoid LS. Specifically, a power reserve of 127 MW, equivalent to the DSR-20 configuration, has resulted in being enough to avoid the shedding of 707 MW, keeping the frequency within the normal operating condition limits.

TABLE III. SIMULATION RESULTS.

Event	Configuration		
	Base	**RES**	**DSR**
	High Export		
Out. of 1 link w. c. Italy	Strongly stable	Strongly stable	Not required
Out. of 2 links w. c. Italy	Strongly stable	Strongly stable	Not required
Generation out. (250 MW)	Strongly stable	Strongly stable	Not required
Generation out. (815 MW)	Strongly stable	Strongly stable	Not required
	High import		
Out. of 1 link w. c. Italy	Strongly stable	Strongly stable	Not required
Out. of 2 links w. c. Italy	Stable thanks to LS	Stable thanks to LS	With DSR-25, DSR-50 and DSR-70, LS is reduced but not avoided
Generation out. (660 MW)	Strongly stable	Strongly stable	Not required
	High load		
Out. of 1 link w. c. Italy	Strongly stable	Strongly stable	Not required
Out. of 2 links w. c. Italy	Strongly stable	Strongly stable	Not required
Generation out. (337 MW)	Strongly stable	Strongly stable	Not required
	Low load		
Out. of 1 link w. c. Italy	Strongly stable	Strongly stable	Not required
Out. of 2 links w. c. Italy	Strongly stable	Strongly stable	Not required
Generation out. (337 MW)	Strongly stable	Strongly stable	Not required
	Lines out of services		
Out. of 1 link w. c. Italy	Strongly stable	Strongly stable	Not required
Out. of 2 links w. c. Italy	Strongly stable	Strongly stable	Not required
Generation out. (337 MW)	Strongly stable	Strongly stable	Not required
	Island		
Generation out. (127 MW)	Strongly stable	Strongly stable	Not required
Generation out. (210 MW)	Stable thanks to LS	Stable thanks to LS	With DSR-20: strongly stable

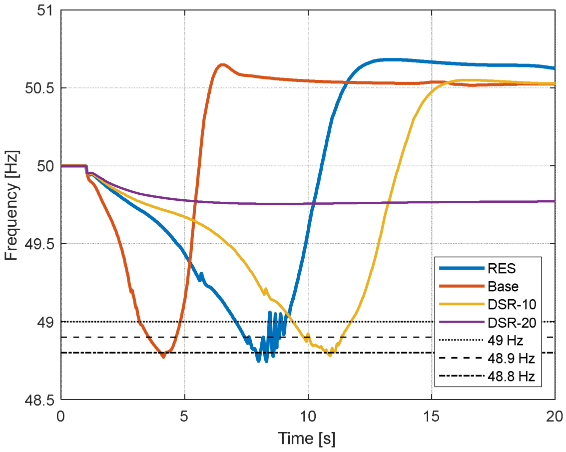

Fig. 2. Frequency profiles in the **Island** dispatching profile, after the loss of 210 MW of generated power.

A second critical situation has been detected in the **High Import** profile. Here, the outage of two of the three connections with continental Italy causes the outage of the third line and, consequently, the islanding of Sicily, with the loss of 1100 MW of power import. It is worth remarking that such a situation is, from a TSO perspective, very unrealistic and can hence be considered as a stress test for the power system in order to check if the flexibility resources considered can even solve this event during the actual operation of the network. Indeed, it happens that the disconnection of two cables leads the current of the third cable to overcome the rated value. In this condition, we assumed that an overcurrent protection was installed (which is not present in the real Italian network), leading to its trip and causes the islanding of Sicily: this would be actually a N-3 condition.

Fig. 3 shows the detailed results of this simulation. After the islanding, frequency stability is guaranteed by LS, and the contribution of SI provided by wind generators results to be more evident (blue line). Indeed, without SI, the frequency derivative is significantly high (red line); all the levels of LS are activated (953 MW). Differently, with the provision of SI, LS is reduced to 738 MW. As for the **Island** profile, the contribution of DSR has resulted in being useful to reduce the frequency derivative and the maximal frequency deviation: LS is not avoided but reduced to 523 MW.

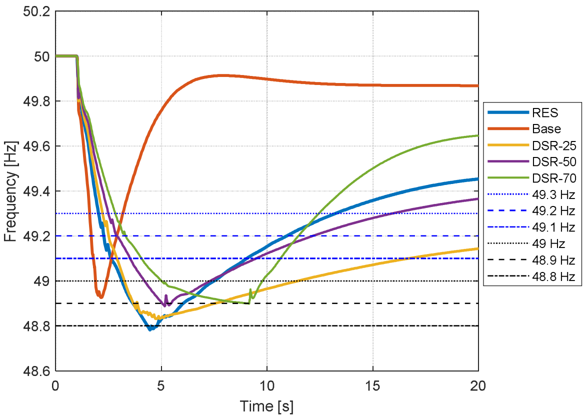

Fig. 3. Frequency profiles in the **High Import** dispatching profile, after the outage of two of the three links with continental Italy.

IV. SMALL PERTURBATION STABILITY ANALYSIS: METHODOLOGY AND RESULTS

The small perturbation stability analysis evaluates the dynamic of the generators in response to a small variation in loads and generation that occurs continuously on the power systems and not necessarily related to a transient disturbance. This kind of instability can be related to the lack of either synchronizing torque or damping torque. Nowadays, this instability mostly concerns the insufficient damping of the system's oscillations, related to large groups of closely coupled machines connected by weak tie lines [3]. The small perturbation angle stability of the Sicilian network has been analyzed for the six selected dispatching profiles of 2030. The modal analysis has been performed focusing on the electromechanical modes with a damping ratio (ζ) below 10%, being the conservative threshold, and below 5%, being the critical one. Electromechanical modes can be identified as those modes in which rotor angle deviation and rotor speed deviation of the generators have a large participation factor. However, only the magnitude of the participation factor carries relevant information. For this reason, it is useful to define the oscillation vector, which is composed of the participation factor magnitude and the angle of the observability vector [11]. Plotting the oscillation vectors of the modes allows identifying their characteristics and the involved generators. The angle differences between the oscillation vectors show how the oscillations are manifested in the rotor speed deviations, e.g., if in phase or counter-phase with each other. In formulas, the oscillation vector of state variable x_i with respect to mode k is:

$$ov_{ki} = |pf_{ki}| \angle w_k(i) \tag{2}$$

where pf_{ki} is the participation factor of state variable x_i in the k^{th} mode and $w_k(\mathrm{i})$ is the i^{th} element of the observability vector k (i.e., the right eigenvector associated to mode k).

The small perturbation stability analysis has been performed, in the identified operating conditions, comparing the "*base case*" with the "*RES case*". In the *base case*, inertial and frequency response are provided just by the synchronous generators. In Fig. 4 the location of the synchronous generators plants is shown. In the *RES case*, also Full Converter Wind Turbines (FCWT) provide synthetic inertia support, and the PSS gains of the generators have been finely tuned. The results are reported in Tables IV to VI, respectively for the **High Export**, **High Import** and **Low load** dispatching profiles. A checkmark indicates a damping ratio above 10%.

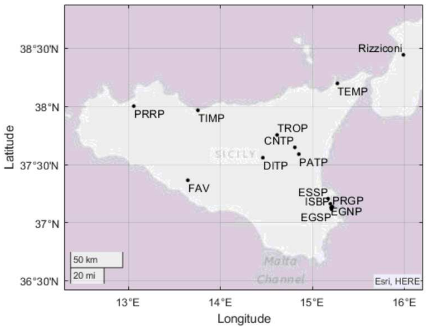

Fig. 4. Locations of the synchronous machines in the Sicilian network. The slack generator is located on the peninsula in the substation of Rizziconi.

The modal analysis shows that mode M1 is the only interarea mode of the system, and it mainly involves the units of the TIMP power plant oscillating against the slack in Rizziconi. In the *base* case, this mode is critical and has a damping ratio below 5%; its damping will be of primary focus throughout the study. In Fig. 5 the oscillation vector of mode M1 is shown. Modes M2 to M5 are either local or interplant modes (involving units of the same plant) associated with synchronous generators within Sicily.

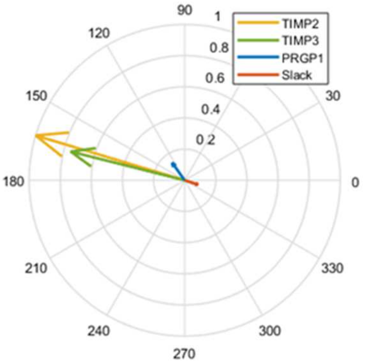

Fig. 5. Oscillation vector of interarea mode M1.

The results show (the *base* case of Table IV, Table V, and Table VI) that, regarding the stability to small perturbations, the system does not present major stability issues. The **High export** dispatching profile is the only one that presents a not properly damped oscillatory mode: mode M1, modeling the oscillations between Sicily and the Italian peninsula, and its stability can be improved thanks to the synthetic inertia contribution provided by wind farms and by tuning the relevant PSSs. In the *base* case, the **Low Load** and the **High Import** dispatching profiles present, respectively, one and two electromechanical modes with damping ratios above 5% and below 10%, thus already properly damped. The other dispatching profiles that is **High load**, **Island** and **Lines out of service** do not present any oscillatory mode with a damping ratio below 10%. Hence, they do not present any stability concern regarding small perturbations.

The contribution of synthetic inertia provided by FCWT, and PSS tuning has been assessed both separately and together. The results of this sensitivity analysis of the eigenvalues with respect to the synthetic inertia gain and PSS gain are shown in Table IV, Table V and Table VI as "*RES Case*". In the *RES* case, mode M1 in the **High export** DP and all the electromechanical modes of the **Low Load** and **High Import** DPs get properly stabilized. The stability of poorly damped modes can be improved above the critical level just by SI alone, but in order to increase most of the damping ratio above the conservative threshold of 10%, retuning the PSSs for the forecasted network configuration is necessary.

In conclusion, in 2030, the Sicilian grid shows very good small perturbation stability features that can be further improved thanks to the synthetic inertia contribution of RES.

TABLE IV. COMPARISON BETWEEN THE BASE AND THE RES CASE FOR THE **HIGH EXPORT** DISPATCHING PROFILE.

Case	M1		M2		M3		M4	
	f (Hz)	ζ $(\%)$	f (Hz)	ζ $(\%)$	f (Hz)	ζ $(\%)$	f (Hz)	ζ $(\%)$
Base	0.7	1.0	1.3	7.5	0.9	8.1	1.6	8.8
RES	✓	✓	1.3	7.3	1.0	9.0	1.6	8.8

TABLE V. COMPARISON BETWEEN THE BASE AND THE RES CASE FOR THE **HIGH IMPORT** DISPATCHING PROFILE.

Case	M1		M3	
	$f\,(Hz)$	$\zeta\,(\%)$	$f\,(Hz)$	$\zeta\,(\%)$
Base	0.7	7.2	0.9	7.4
RES	✓	✓	✓	✓

TABLE VI. COMPARISON BETWEEN THE BASE AND THE RES CASE FOR THE **LOW LOAD** DISPATCHING PROFILE.

Case	M5	
	$f\,(Hz)$	$\zeta\,(\%)$
Base	1.7	9.5
RES	✓	✓

V. VOLTAGE STABILITY: METHODOLOGY AND RESULTS

The voltage stability is a steady-state analysis (i.e., slow dynamics considered) aimed to identify the maximum loading conditions keeping acceptable voltages at all busses (e.g., between the 0.9 and the 1.1 of the per-unit rated voltage) after being subjected to disturbances. A system enters a state of voltage instability when a disturbance, like a slow increase of load or a change in the system conditions, causes a progressive and uncontrollable voltage decline. The main factor causing instability is the inability of the power system to provide reactive support [3], like:

- high load on the transmission system;
- voltage sources far from the load centres;
- insufficient reactive compensation.

For this work, first, the voltage stability analysis has been carried out considering the possibility that the reactive support is initially given only by the synchronous generators in service; then, the RES power plants have been assumed to be equipped with specific devices and controls, adopted by Terna in the Italian grid code [12][13][14], for the reactive provision and a second set of tests has been carried out. Finally, to improve the voltage levels in particularly weak grid conditions, a sensitivity analysis of the parameters of the RES reactive controllers has been performed and compared with the initial (base) case. The PV curve calculation available in DIgSILENT program has been used and adapted for this research to carry out the voltage stability analysis. Basically, it performs a PV curve calculation and finds the critical points of voltage instability by increasing the power demand of loads until the load flow calculation no longer converges, i.e., until the voltage stability limit is determined.

The 400 kV HV busbars of Sicily have been monitored; in particular, their voltage magnitudes have been examined to fulfil the 0.9 - 1.1 p.u. limits. Zero and negative loads have not been considered for this evaluation; at each iteration, the active power demand of the remaining loads was increased by small steps. In the base case, the synchronous machines provided the additional active, and reactive demand requested till their capability limits had been reached. Reactive support of the RES is also considered: the current capability limits specified by Terna in [12][13] have been implemented (Fig. 6, solid red line). In detail, the maximum/minimum reactive support must be equal to ± 35% of the active power available.

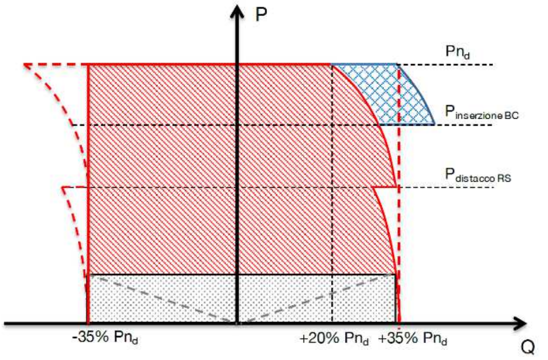

Fig. 6. Capability curve implemented for wind and PV plants [12][13].

The Sicilian network provided by Terna, in its base case, presents a quite high loadability margin, equal to 65%. For these studies, this value will be used as a reference value, but loadability equal/higher than 40% has been considered acceptable as well. Fig. 7 shows the results obtained for all the six profiles selected.

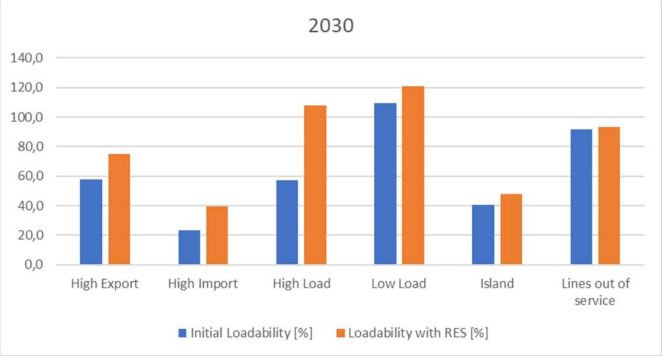

Fig. 7. Loadability margins for the 2030 [%].

It has been noticed that when Sicily is importing power from continental Italy or its power demand is high its loadability margin, and hence its voltage stability, is reduced. All the other dispatching profiles present a good loadability margin, in particular the one with very low consumption, where a lot of thermal power plants are dispatched at their minimum power.

Moreover, thanks to the RES equipped with the current standard for the reactive power provision, Sicily presents a quite good loadability margin, at least higher than 40%. Hence, even in the presence of quite high-wind and PV penetration, the voltage stability can be kept.

VI. CONCLUSIONS

This paper reports the main results carried out by ENSiEL for the OSMOSE project within Task 1.4.3. As a conclusion of the task force, ENSiEL showed that relevant dispatching profiles present instability conditions that could only be dealt with by flexibility options available. Namely, synthetic inertia provided by wind turbines and suitable PSS control in one case, and frequency containment reserve provided by demand-side response in the other. Additional flexibility options are only needed in few cases to ensure suitable post-perturbation conditions. In general, the system snapshots studied were already stable without considering any additional flexibility options. Moreover, the contribution in terms of voltage control from RES-based generation has been found necessary to avoid low voltage profiles.

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