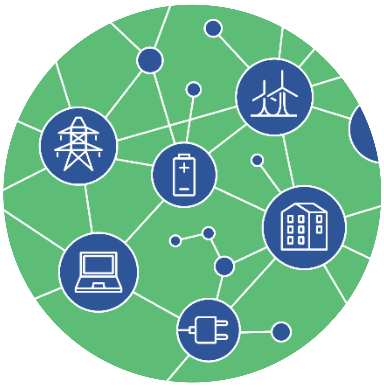
OSMOSE

OPTIMAL SYSTEM-MIX OF FLEXIBILITY SOLUTIONS FOR EUROPEAN ELECTRICITY

Stability Aspects

Internal Deliverable T1.4.3



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0 Executive summary

This report presents the internal deliverable Stability Aspects, within the scope of the work performed by ENSiEL under T.1.4.3. Here, a brief description of the simulation tool, models and the studies performed are presented.

WP1 focuses on the Optimal Mix of Flexibilities, starting by proposing long-term scenarios (2030 and 2050), which differ on demand levels, installed capacities, investment options, and on the amount of flexibility options. Static reserve adequacy analysis has been carried-out by RTE using its ANTARES model, aiming to assess and validate these scenarios.

Using data from T.1.1 and T.1.2 as input, ENSiEL has evaluated the impact of innovative flexibility sources (e.g. renewable energy resources, battery energy storage systems and demand-side response) on power system stability, testing them in a significantly large model of the Italian electrical network, provided by Terna, the Italian Transmission System Operator (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.

The given grid has been updated with the new values of capacities and loads given by T 1.1, for years 2030 and 2050. Capacities of the "*Current Goal Achievement*" scenario are implemented for years 2030 and 2050 related to the generators and the following most typical and critical generation/demand conditions have been tested:

- very low load/very low rotating generation in operation;
- high load/low rotating generation in operation;
- maximum export/import of areas;
- operational conditions with weak network (e.g. lines out of service);
- islanding conditions.

The following topics have been then investigated:

- Large-perturbation angle and frequency stability;
- Small-perturbation angle stability;
- Voltage stability.

As main conclusions for *2030*, a couple of cases showed 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. In a few cases, additional flexibility options are needed to ensure suitable post-perturbation conditions. In all other cases, the system snapshots studied were already stable without considering additional flexibility options. Further to the above mentioned options, also contribution in terms of voltage control from RES-based generation are required to avoid low voltage profiles.

Concerning the scenario *2050*, the increased penetration of RES-based generation makes the system conditions closer to instability. However, all operating conditions studied do not show unsolvable stability problems. Furthermore, flexibility options in 2050 seems to be much more necessary to stabilize the system in a higher number of cases. The 2050 scenario is nevertheless characterized by the massive presence of flexibility options provided by RES, as well as by a more significant presence of energy storage, that provides further control variables.

All those considered, the studies carried out make it possible to conclude that such a suitable mix of flexibility options should be adequate to keep the dynamic system security.

1 List of acronyms and abbreviations

You can find in the table below the list of the acronyms and abbreviations used in this document.

Acronym/Abbreviation	Meaning
ATC	Available Transfer Capacity
AVR	Automatic Voltage Regulator
BESS	Battery Energy Storage System
CC	Combined Cycle
DFIG	Doubly-Fed Induction Generator
DSR	Demand Side Response
FCR	Frequency Containment Reserve
FCWT	Full Converter Wind Turbine
FFR	Fast Frequency Regulation
GOV	Governor
GT	Gas Turbine
HV	High Voltage
IR	Inertia Response
LV	Low Voltage
MC	Monte Carlo
MV	Medium Voltage
P2G	Power-to-Gas
PFR	Primary Frequency Response
PSS	Power System Stabilizer
PV	Photovoltaic
RES	Renewable Energy Source
SI	Synthetic Inertia
TSO	Transmission System Operator
WP	Work Package

2 Introduction

This report presents internal deliverable Stability Aspects, which ENSiEL (Politecnico di Milano, University of Genova, and University of Bologna) is responsible for within WP1 and its sub-task 1.4.3 – Stability Aspects. In this task, ENSiEL has to evaluate the impact of innovative flexibility sources on power system stability, mainly with reference to the services identified by Subtask 1.1.2 [1].

The dynamic stability has been assessed versus some typical perturbations of power systems, e.g., loss of a large generator or slow increase of loads, contingencies of branches, etc., by developing and implementing suitable models of power system components and controls in DIgSILENT PowerFactory. Two time-horizons are considered, i.e., 2030 and 2050; selected scenarios (for what capacity of different sources and loads, and total energies are concerned) provided by T.1.1 [2], and dispatching profiles resulting from T.1.2 [3] have been considered for simulations.

In order to be able to carry out suitable dynamic simulations, a significantly large model of the electrical network has been provided by Terna, the Italian Transmission System Operator (TSO), according to some restrictions for what disclosure of data is concerned, with reference to a portion of the Italian system [4]. This grid model has been updated according to both the capacities defined by the scenarios provided by Task 1.1 (and corresponding decommissioning of some old units), and the system-wide balancing of energy supply and demand identified area by area by Task 1.2 [2]. Therefore, the goal of T.1.4.3 is to assess if the outputs of the above-mentioned Tasks are feasible from a dynamic point of view, to identify in time possible lack of stability and in such a case, to suggest possible countermeasures, picking up any flexibility resource that can be useful.

In the present document, the output of all detailed simulations of the electrical system carried out are presented and described. In particular, the following topics have been investigated:

- Large-perturbation angle and frequency stability: this assessment determines the generators response to the changes in frequency and voltage in a time scale from tens of milliseconds up to 4/5 seconds, where angle stability can be evaluated, considering both generator and load dynamics;
- Large angle stability typically involves the study of large transients and how the power output of the synchronous machines varies as their rotors are moving. The goal is to evaluate if the synchronous machines can be kept in synchronism after a fault, a change in the transmission topology or a disconnection of a large generating unit, so involving a severe transient disturbance [5];
- Small-perturbation angle stability: this assessment 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. Currently, this instability mostly concerns the insufficient damping of the systems oscillations, related to large groups of closely coupled machines connected by weak tie lines [5];

- Voltage stability: this assessment estimates the voltage variation during a slow increase of loads active power demand. Voltage stability is 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 [5].

3 Grid model – Sicily Island

The grid model employed for testings is a portion of the Italian transmission network (Figure 1) corresponding to Sicily; basic data have been provided by Terna. Sicily is identified by the market zone *56IT* (T.1.1 [2] and T.1.2 [3]).

Regarding the grid configuration, Sicily presents few lines with a voltage higher or equal to 220 kV and, considering the geographic dimension and the high amount of generation capacity installed, they are 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 by two parallel AC undersea cables. The 400 kV system (in red in Figure 1) essentially consists in a single backbone starting from the just mentioned link in the extreme 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. Primary transmission system is made by a big 230 kV ring, extended along the coastal territories with a double circuit (in green in Figure 1).

Figure 1. Sicilian HV grid [6].

Regarding the installed conventional generators, Figure 2 reports the major thermal power plants of Sicily in 2020:

Plant	Owner	Type and rating
Anapo (SR)	ENEL	Storage hydro, 500 MW
Augusta (SR)	ENEL	Fossil fuel thermal, 210 MW
Priolo Gargallo Nuce Nord (SR)	ERG	CCGT thermal, 480 MW
Priolo Gargallo ISAB Energy (SR)	ERG	IGCC thermal, 528 MW
Priolo Gargallo Archimede (SR)	ENEL	CCGT thermal, 750 MW
Trapani (TP)	E.ON	Gas turbine, 169 MW
Gela (CL)	Eni	Fossil fuel thermal, 260 MW
San Filippo del Mela (ME)	Edipower	Fossil fuel thermal, 1280 MW
Milazzo (ME)	Edison/Eni	CCGT thermal, 365 MW
Termini Imerese (PA)	ENEL	CCGT thermal, 1340 MW

Figure 2. Sicily major thermal and PSP power plants [7] - [14] (2020).

In Rizziconi substation, end of this link in the continent, a frequency relay is installed which is able to disconnect the Island from the rest of the system in particular critical conditions. Usually, during normal operation, Sicily exports to Italy a large amount of active power. This is done with the purpose to keep the Sicilian power system in operation in case of the trip of the interconnection, thus avoiding load shedding in 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:

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

This also explains why Sicily is usually exporting power. Indeed, if the Island was importing during an under frequency event, a disconnection could worsen the power deficit, accelerating the frequency decay. Sicilian four large pumping units of Anapo plant are always disconnected as a first solution, if they are operating in pumping mode.

In case of under frequency events, moreover, a load shedding scheme is in operation, and its settings are shortly described in Table 1; according to different thresholds, a load shedding step can be activated, as described.

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 %

Table 1. Load shedding settings [15].

3.1 Data scenario application

The scope of Subtask 1.4.3 is to simulate the dynamical stability of the Sicilian grid with different mix of loads and generation deployment coming from T.1.1 and T.1.2 to evaluate possible security issues and possibly suggestion for countermeasures.

3.1.1 Capacities and Loads

The Sicilian grid has been updated with the new values of capacities and loads given by Task 1.1, area by area, for years 2030 and 2050. Each scenario identified in Task 1.1, "*Accelerated Transformation*", "*Current Goals Achievement*" and "*Neglected Climate Action*", provides data for the 99 European zones defined by *e-Highway 2050*. In detail, for each zone the total installed generation capacity, differentiated by primary sources (biomass, geothermal, wind, solar, gas and hydro), is given, as well as the total load installed.

As described in [16], T.1.1 provided the capacity, differentiated by technology, for each European market zone, either connected to the HV or MV grids; that capacity has 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 web site with the technical characteristics of all plants connected to the Italian transmission system [17]. Table 2 shows the current RES deployment in Sicily (2020) and the percentage connected to either MV or HV level; it is clear that the photovoltaic plants are almost connected to the distribution grid, while the wind and hydro plants to the transmission one. Such percentages have been used to share the RES data provided by TUB, while some conventional thermal plants have been simply switched off, to mimic their decommissioning as RES take over. The Power to Gas (P2G) technology has been considered as a repowering of some of the old thermal plants and located accordingly, biogas (bioenergy) and waste-to-energy technologies have been modelled assuming they are brown field.

Technology	Total Installed [MW]	MV connected [%]	HV connected [%]
Photovoltaic	1422	97.00	3.00
Wind	1887	6.00	94.00
Hydro	274	4.00	96.00

Table 2. Current RES installed in Sicily (beginning of 2020) [17].

3.1.2 Testing of typical generation/demand conditions – dispatching profiles

In T.1.4.3 only the scenario "*Current Goal Achievement*" is considered, as dispatching profiles are not available for the other two scenarios.

Capacities of the "*Current Goal Achievement"* scenario are implemented for years 2030 and 2050 related to the generators; the following most typical and critical generation/demand conditions have been tested, with reference to Sicily:

- very low load/very low rotating generation in operation;
- high load/low rotating generation in operation;
- maximum export/import of areas;
- operational conditions with weak network (lines out of service);
- islanding conditions.

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

From T.1.2, the level of generation, differentiated by the primary sources, the active power demand, and the import (or export) in MW for each hour of one entire year are available.

To achieve the aforementioned critical conditions, the profiles provided have been carefully analysed and the most appropriated hours, considered to better resemble the desired situations, have been picked up. Reactive power is not taken into account by Task 1.2, so, to keep a realistic load behavior, typical values of power factor, based on the characteristics of Italian power system, have been assigned to the loads of Sicilian zone.

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. To achieve the desired values, the current active power set points of the HV loads have been adjusted using a suitable scaling factor to increase, or decrease, the total demand.

3.1.3 2030 Network

The following changes have been applied for 2030 using the data provided by TUB and showed in Table 3:

- power rating of the links with the mainland has been increased according to the Available Transfer Capacity (ATC) data for 2030;
- an equivalent synchronous machine has been installed close to the continental terminal of the link Sicily-continental Italy to reasonable reproduce the dynamic behaviour of the rest of the Italian system. Its rated power equals the sum of the active power of the synchronous machines of the other Italian market zones at the time frame considered, divided by a power factor (0.8), and starting time constant equal to 10 s. This approach is conservative, in the sense that the equivalent machine represents only a portion of the generating units of the continental Italy able to provide primary frequency control;

it is equipped with a governor, an automatic voltage regulator and a power system stabilizer properly tuned;

- the wind model [16], able to provide synthetic inertia, has been assumed to be installed on the currently (2020) present 20 wind farms;
- already existing HV Photovoltaic (PV) plants have been modelled according to [16], including its LV/MV transformer. The same PV model has been considered installed at the MV busbars of the 285 primary substations to mimic the contribution of the dispersed generation connected to the distribution grids. All photovoltaic models are equipped with the over frequency protections, set according to the Italian standards [15][18];
- capacities of all generators have been upgraded according to the data provided by T.1.1;
- no batteries have been considered, since their installations is not expected in 2030 in T1.1.

Zone	Battery	Biomass	PV	Hydro	Wind	Waste	Gas
56IT	0	99	2618	242	3820	781	2896

Table 3. Installed capacity [MW] provided by TUB for 2030 for Sicily [2].

The dispatching profiles (in the following also referred as "*hourly profile*" or simply "*profile*") considered in the stability analysis of Sicily are:

1. *High Export*: represented by 22nd of March of Monte Carlo (MC) year 4 at 8.00 a.m., characterized by quite high PV, but low traditional generation production;
2. *High Import*: represented by 9th of April of MC 1 at 7:00 p.m., characterized by almost zero PV production and high load demand; such active power request is provided by rest of Italy;
3. *High Load / Low Gas*: represented by 19th of June of MC 1 at 9:00 a.m., characterized by high load demand; high PV, medium wind and low traditional generation production.
4. *Low Load / Low Gas*: represented by 21st of August of MC 1 at 2 a.m., characterized by low load and low generation by thermal plants, dispatched at their minimum active power, and medium wind production;
5. *Island*: it is the *High Load / Low Gas* profile, with the link with the mainland out of service;
6. *Lines out of service*: it is the *Low Load / Low Gas* profile with the following 230 kV lines out of service: Favara_Chiaramonte and Caracoli_Sorgente.

A detailed description of these six dispatching hourly profiles is reported in Table 4:

Dispatching profile	High Export	High Import	High Load / Low Gas	Island	Lines out of service	Low Load / Low Gas
Time	22/03/2030 08:00	09/04/2030 19:00	19/06/2030 09:00	19/06/2030 09:00	19/06/2030 09:00	21/08/2030 01:00
MC Year	4	1	1	1	1	1
Zonal export [MW]	604	-1100	8	0	-576	-576
			Loads			
Total Load [MW]	3101	3075	2944	2944	1841	1841
Traditional load [MW]	3101	3075	2944	2944	1841	1841
DSR Electrical Vehicle [MW]	0	0	0	0	0	0
Pumping [MW]	0	0	0	0	0	0
Electrolyser [MW]	0	0	0	0	0	0
Battery Storage [MW]	0	0	0	0	0	0
DSR Heat Pump [MW]	0	0	0	0	0	0
			Generation			
Total Generation [MW]	3705	1975	2952	2952	1265	1265
ROR [MW]	14	20	25	25	19	19
WIND [MW]	216	245	153	153	232	232
SOLAR [MW]	1321	0	2060	2060	0	0
NUCLEAR [MW]	0	0	0	0	0	0
COAL [MW]	0	0	0	0	0	0
GAS[MW]	1740	1120	300	300	600	600
BATTERY [MW]	0	0	0	0	0	0
PSP [MW]	0	4	0	0	0	0
P2G [MW]	0	0	0	0	0	0
CHP [MW]	0	0	0	0	0	0
BIO-ENERGY [MW]	414	414	414	414	414	414
H. STOR [MW]	0	172	0	0	0	0
SPIL. ENRG [MW]	0	0	0	0	0	0
UNSP. ENRG [MW]	0	0	0	0	0	0
			Continental Italy Equivalent Generator			
NOMINAL POWER [MVA]	34391	37723	19069	19069	16554	16554

Table 4. 2030 dispatching profiles [MW] [3].

3.1.4 2050 Network

In the following, the major changes applied to the 2030 grid to meet 2050 data of TUB showed in Table 5 are described:

- power rating of the cables with the mainland have been increased to meet the ATC data provided of 2300 MW;
- beside the wind plants already existing and equipped with a controller able to provide synthetic inertia, another wind model [16], capable to provide fast frequency response, has been connected to the 230 kV system for an additional installation of 15 plants;
- as in 2050 installation of batteries has been nonzero, according to T1.1, the battery model [16], able to provide primary frequency control, has been considered. Batteries are installed either near each new wind plant or at the sites of the few synchronous generators not decommissioned. The total amount of storage power has been installed according to T1.1.; it has been located assuming that each site is equipped with a maximum of 20% of the capacity of the already installed generation plant;
- controlled loads [16], able to provide both frequency and voltage control, have been installed near 16 already existing loads considered large enough (at least 13 MW);

- the 220 kV ring circuit of the Island has been doubled, even if no indications regarding the zonal grid reinforcements are given by the other Tasks. This has been done to accommodate the demand expected for 2050;
- capacities of all generators have been upgraded according to the data provided by T1.1, using the same approach of 2030;
- The equivalent synchronous machine in continental Italy has been updated as well; its rated power equals the sum of the active power of the synchronous machines of the other Italian market zones at the time frame considered, divided by a power factor (0.8).

Zone	Battery	PV	Hydro	Wind	Waste	Gas	P2G
56IT	1572	6075	313	6360	566	162	1947

Table 5. Installed capacity [MW] provided by TUB for 2050 for Sicily [2].

Finally, the following dispatching profiles, derived by the data provided by RTE, have been picked up and implemented for the 2050 Sicilian grid:

1. *High Export*: represented by 24th of May of MC 4 at 2:00 a.m., characterized by quite high wind production, no photovoltaic and low load demand;
2. *High Import*: represented by 11th of January of MC 1 at 1:00 a.m., characterized by almost no renewable production and medium/high demand;
3. *High Load*: represented by 27th of May of MC 1 at 4:00 p.m., characterized by high load demand, high wind and photovoltaic production;
4. *Island*: represented by the 23rd of June of MC 5 at 3:00 p.m., with high photovoltaic and wind production and the link with the mainland out of service;
5. *Low Load*: represented by the 4th of June of MC2 at 2:00 a.m., characterized by low load and almost zero wind production;
6. *Lines out of service*: it is the *Low Load* profile with the Favara_Chiaramonte and Caracoli_Sorgente 230 kV lines out of service.

A detailed description of these six dispatching hourly profiles is reported in Table 6:

Dispatching profile	High Export	High Import	High Load	Island	Low Load	Lines out of service
Time	24/05/2050 02:00	11/01/2050 01:00	27/05/2050 16:00	23/06/2030 15:00	04/06/2050 02:00	04/06/2050 02:00
MC Year	4	1	1	5	2	2
Zonal export [MW]	725	-1188	0	0	-578	-578
			Loads			
Total Load [MW]	1837	3218	4099	4294	1514	1514
Traditional load [MW]	1837	3218	2318	2500	1514	1514
DSR Electrical Vehicle [MW]	0	0	0	0	0	0
Pumping [MW]	0	0	0	0	0	0
Electrolyser [MW]	0	0	1781	1794	0	0
Battery Storage [MW]	0	0	0	0	0	0
DSR Heat Pump [MW]	0	0	0	0	0	0
			Generation			
Total Generation [MW]	2562	2030	4099	4294	936	936
ROR [MW]	30	11	30	25	25	25
WIND [MW]	1480	253	2059	1124	195	195
SOLAR [MW]	0	0	1211	2429	0	0
NUCLEAR [MW]	0	0	0	0	0	0
COAL [MW]	0	0	0	0	0	0
GAS[MW]	0	0	0	0	0	0
BATTERY [MW]	786	0	0	0	0	0
PSP [MW]	0	0	0	0	0	0
P2G [MW]	0	1500	533	450	450	450
CHP [MW]	0	0	0	0	0	0
BIO-ENERGY [MW]	266	266	266	266	266	266
H. STOR [MW]	0	0	0	0	0	0
SPIL. ENRG [MW]	0	0	0	0	0	0
UNSP. ENRG [MW]	0	0	0	0	0	0
			Continental Italy Equivalent Generator			
NOMINAL POWER [MVA]	10411	14934	23053	9607	13533	13533

Table 6. 2050 dispatching profiles [MW] [3].

4 Large perturbation angle and frequency stability analysis

This chapter summarizes the results carried out by ENSiEL (in particular, University of Genoa) for the OSMOSE project, WP1, subtask 1.4.3.

In the following, first the definition of frequency stability is reminded and then all simulation results are shown.

4.1 Frequency stability definition

According to the Italian grid code [19], frequency should be kept within the range 49.9 Hz – 50.1 Hz in *normal operating condition*. For the special case of Sicily, when in its operation it is disconnected from the Italian peninsula, the normal condition range is assumed to be 49.5 Hz – 50.5 Hz. In *emergency operating condition*, frequency should remain in the range 47.5 Hz – 51.5 Hz. According to [20], if the frequency exceeds the emergency condition range of 47.5 Hz or 51.5 Hz, a system blackout can hardly be avoided.

To analyse the simulation results, which refer to the study case of Sicily, the following rules, implemented by the Italian TSO, should be considered:

- the Sicilian Islanding relay, as described in Section 03;
- load Shedding scheme: realized according to the settings reported in Table 1.

4.2 Large perturbation events

To study large perturbation stability a set of events are simulated in each of the dispatching profiles defined for Network 2030 and Network 2050. In particular, three classes of events are simulated:

- outage on one or two connections between Sicily and continental Italy;
- outage of sets of generating units: in this case, for each event, we will indicate the power plant total nominal power (Snom) and the imbalance shown will be the current operating point output (MW) of all involved units. Since in Network 2050 we assumed that BESSs are installed at all generation sites, generation unit outages simulated will also consider to trip both the unit and the relevant BESS. In this case, the reported nominal apparent power (Snom) and amount of generated power imbalance will refer to the entire aggregate;
- load-step in continental Italy: in this case, we will indicate the size of the simulated load-step; the load used to generate this perturbation is an equivalent load installed close to the continental terminal of the link Sicily-continental Italy.

4.3 Simulations results

4.3.1 2030 Network

In the forecasted scenario for Sicily in 2030, according to results provided in WP1 [2], **there are no any Demand Side Response (DSR) service provided by loads and no battery storage systems**. Therefore, two main network configurations are considered for each event:

- **base configuration**, which is the configuration designed according to the provided forecasts;
- **no-SI-Wind configuration**, where the Synthetic Inertia (SI) provided by wind generators is disabled.

In order to provide a complete analysis, in the cases where frequency dynamics activate Sicily islanding or load shedding, further network configurations with DSR are simulated (even though it was not assumed in operation according to T.1.1), to check if this flexibility option is useful in that framework to solve any possible unfeasibility showing up and to avoid load shedding. With this aim, a set of 24 DSR models for Fast Frequency Regulation (FFR) services, described in [16] have been added to the DIgSILENT model to the most important loads available (at least 13 MW). In the other dispatching profiles, loads are scaled up with a constant ratio, thus, they can be always considered as the more significant. Table 7 reports the list of the loads associated to the DSR models and their operating points for each hourly profile identified.

	Active Power [MW]					
Name	**High Export**	**High Import**	**High Load/Low Gas**	**Island**	**Lines out of service**	**Low Load/Low Gas**
Load 1	0	0	0	0	13.4	13.4
Load 2	42.8	42.8	42.8	42.8	21.4	21.4
Load 3	27.6	27.6	27.6	27.6	13.8	13.8
Load 4	29	29	29	29	14.5	14.5
Load 5	27.8	27.8	27.8	27.8	13.9	13.9
Load 6	26.6	26.6	26.6	26.6	13.3	13.3
Load 7	0	0	0	0	16	16
Load 8	0	0	0	0	15	15
Load 9	30	30	30	30	15	15
Load 10	126.6	126.6	126.6	126.6	63.3	63.3
Load 11	27	27	27	27	13.5	13.5
Load 12	33.8	33.8	33.8	33.8	16.9	16.9
Load 13	28	28	28	28	14	14
Load 14	0	0	0	0	16.6	16.6
Load 15	30	30	30	30	15	15
Load 16	0	0	0	0	13	13
Load 17	26.8	26.8	26.8	26.8	13.4	13.4
Load 18	52.4	52.4	52.4	52.4	26.2	26.2
Load 19	27.6	27.6	27.6	27.6	13.8	13.8
Load 20	27.2	27.2	27.2	27.2	13.6	13.6
Load 21	29.6	29.6	29.6	29.6	14.8	14.8
Load 22	0	0	0	0	16.6	16.6
Load 23	26.6	26.6	26.6	26.6	13.3	13.3
Load 24	0	0	0	0	14.4	14.4
TOTALS	**619.4**	**619.4**	**619.4**	**619.4**	**414.7**	**414.7**

Table 7. Network 2030. Loads associated with the DSR models.

The following Table 8 reports the values of the parameters of the DSR models common to all loads and kept constant for all simulations carried out.

Parameter	Value	Parameter	Value
T	0.1 s	Ts	0.02 s
dBf	0.02 Hz	T1	0.02 s
bpoint	0.03 Hz	Dfmax	0.2 Hz

Table 8. Frequency control service common parameters values.

According to the Internal Deliverable of T1.4.3 provided by ENSiEL, the parameters in Table 8 are:

- T: the measurement delay time constant [s];
- dBf: frequency dead-band Δf_{DB} [Hz];
- bpoint: frequency dead-band compensation breaking point p [Hz];
- Dfmax: maximum steady-state frequency $\Delta f_{\max}$ [Hz];
- Ts: measurements sampling time [s];
- T1: frequency derivative filter time constant [s].

The values of the following parameters are defined differently in each hourly profile:

- Pres_up: positive Frequency Containment Reserve (FCR) [MW];
- Pres_down: negative FCR [MW] (positive value);
- Ksi_up: synthetic inertia gain for positive frequency deviation [MWs^2];
- Ksi_down: synthetic inertia gain for negative frequency deviation (positive value) [MWs^2];
- Pmax: maximum positive power variation [MW];
- Pmin: maximum negative power variation [MW].

All these parameters are set equal to the same tuning value K_{DSR}. This means that positive and negative FCRs are equal (since Pres_up = Pres_down = K_{DSR}). Moreover, also synthetic inertia is symmetric and, according to Internal Deliverable of T1.4.3, K_{DSR} = Ksi_up = Ksi_down is the power variation provided when frequency derivative is equal to ± 1 Hz/s.

Parameter K_{DSR} for the ith load is defined as a percentage p [%] of the load operating point $P_{L,i}$:

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

Consequently, additional network configurations referred to as DSR-p have been realized, given the value of the percentage p. In the following subsections, where simulation results are provided, the sum of parameters $K_{DSR,i}$ for the considered network configuration K_{DSR}^{tot} is reported: this value is equal to the total amount of DSR FCR. Moreover, the following parameter is also important: **% DSR**, the percentage value of K_{DSR}^{tot} with respect to the total load of the hourly profile.

In the following subsections, results obtained for each dispatching profile are reported.

4.3.1.1 High Export dispatching profile

Here, the events reported in the following have been simulated:

- outage of one of the three connections with continental Italy;
- outage of two of the three connections with continental Italy;
- outage of Priolo Power Plant Gas Turbine 1 (GT1, Snom = 288 MVA): loss of 250 MW of generated power;
- outage of Termini Imerese Combined Cycle (CC) power plant, GT1 and GT2 (Snom = 946 MVA): loss of 815 MW of generated power.

No DSR FCR service has been here considered, since frequency stability is already guaranteed in the base configuration.

4.3.1.1.1 Outage of one of the three connections with continental Italy

The following Figure 3 and Figure 4 report the simulation results obtained with the loss of one of the three connections from continental Italy. It can be observed that frequency stability is always guaranteed, also without the Synthetic Inertia (SI) proved by wind generators. Indeed, the frequency deviation is lower than 4 mHz in both the network configuration cases.

Figure 5 and Figure 6 show the power exchanged through the three connections with continental Italy in the base and No-SI-Wind configurations, respectively. It can be observed that the power exported by the lost connection is distributed to the two remaining connections.

In all the cases, we verified that currents are always lower than the rated value, which is assumed equal to 0.93 kA.

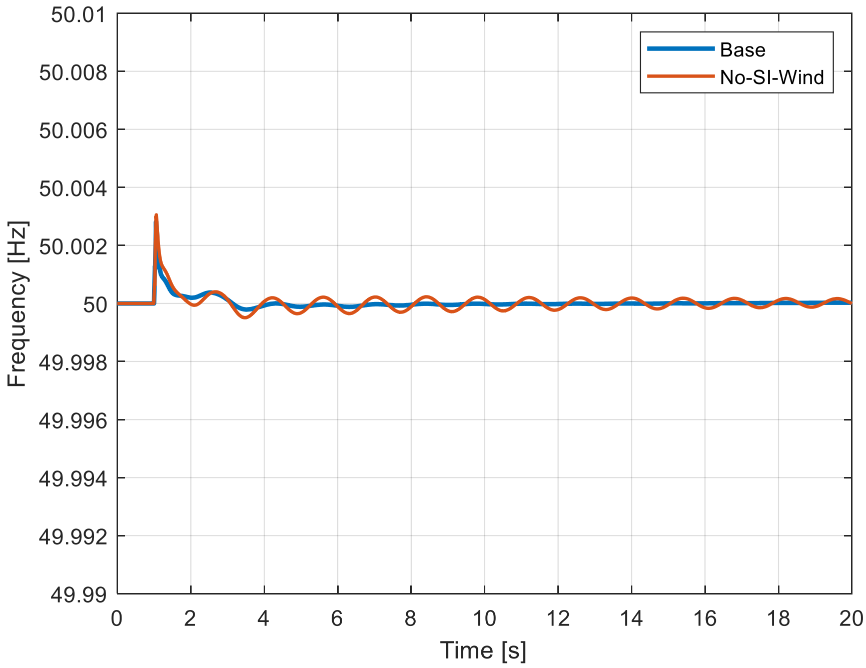

Figure 3. Network: 2030. Dispatching profile: High Export, Event: outage of one of the three connections with continental Italy. Frequency profiles.

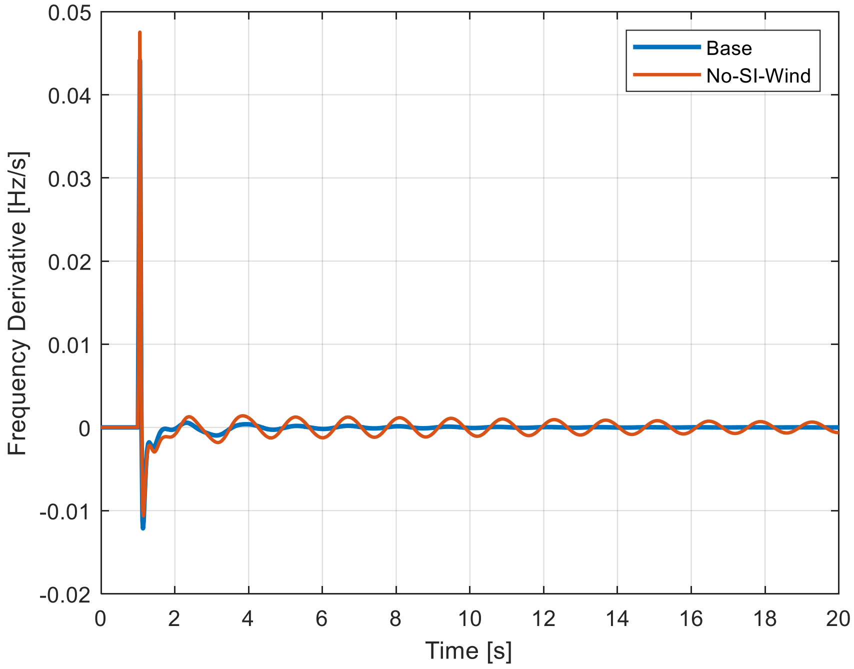

Figure 4. Network: 2030. Dispatching profile: High Export, Event: outage of one of the three connections with continental Italy. Frequency derivative profiles.

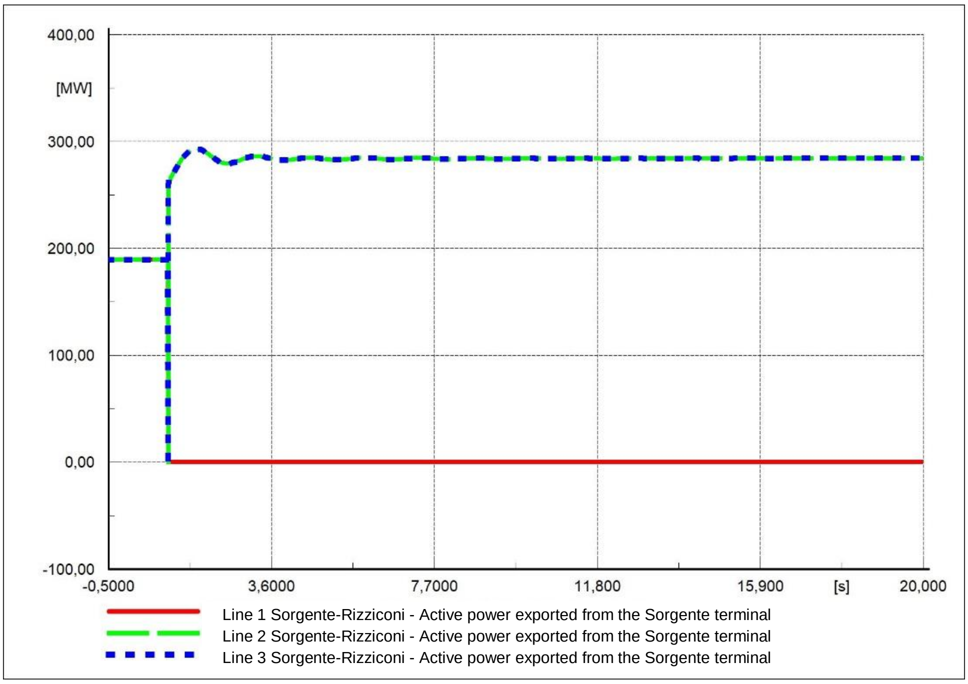

Figure 5. Network: 2030. Dispatching profile: High Export, Event: outage of one of the three connections with continental Italy, base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

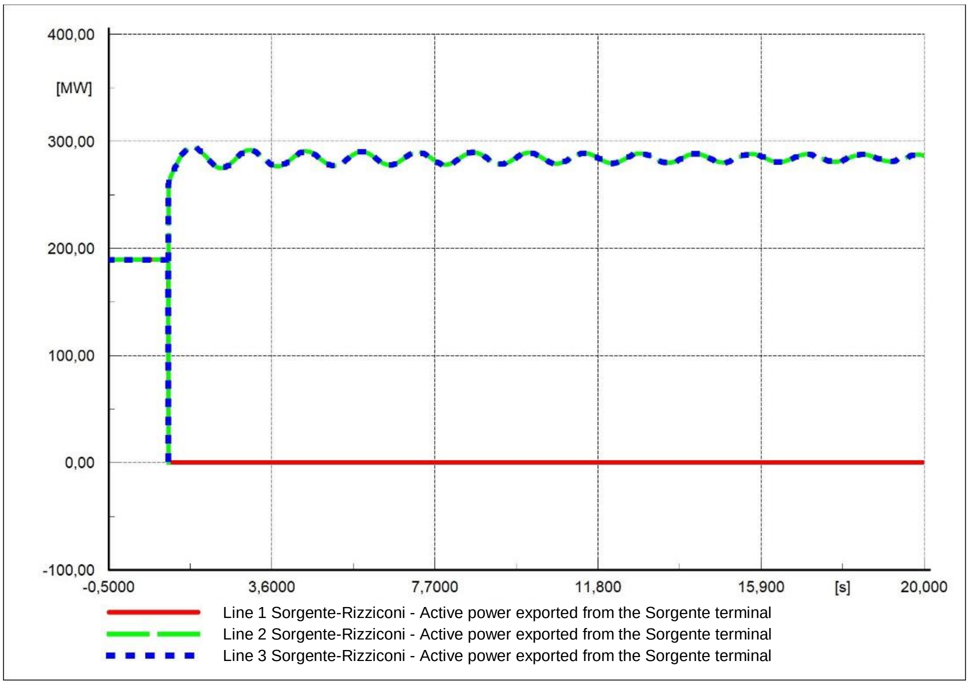

Figure 6. Network: 2030. Dispatching profile: High Export, Event: outage of one of the three connections with continental Italy, No-SI-Wind configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.1.2 Outage of two of the three connections with continental Italy

The following Figure 7 and Figure 8 report the simulation results obtained with loss of two of the three connections with continental Italy. In this case, frequency stability is guaranteed both with and without the Synthetic Inertia (SI) provided by wind generators. Frequency deviation is higher with respect to the case with the loss of only one connection, as expected. However, it is worth observing that, without the SI provided by wind generator, an oscillation of frequency not very well damped occurs.

Figure 9 and Figure 10 show the power exchanged through the three connections with continental Italy in the base and No-SI-Wind configurations, respectively. It can be observed that the power exported by the lost connections is entirely exported by third one.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 0.93 kA.

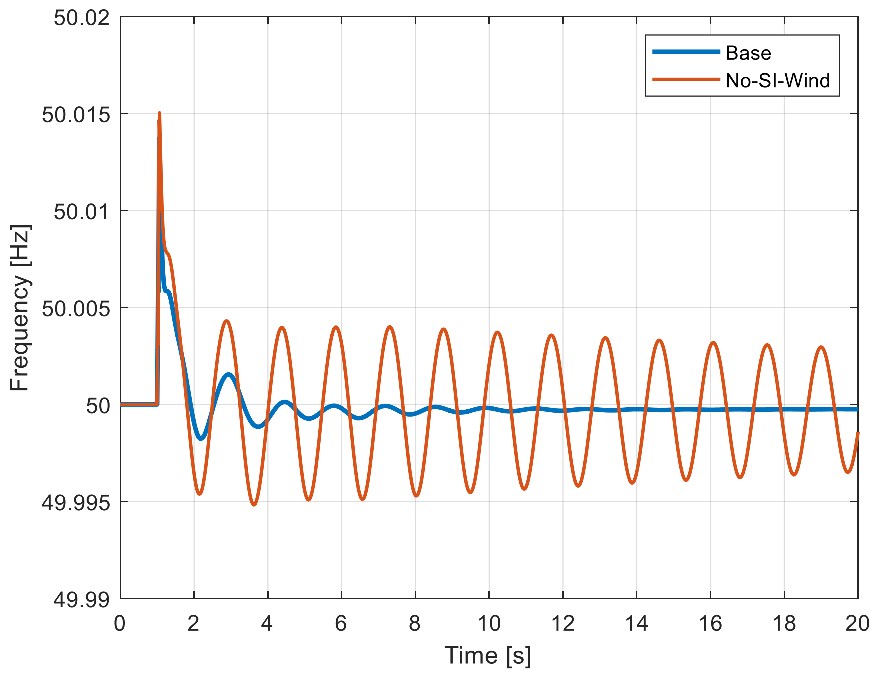

Figure 7. Network: 2030. Dispatching profile: High Export, Event: outage of two of the three connections with continental Italy. Frequency profiles.

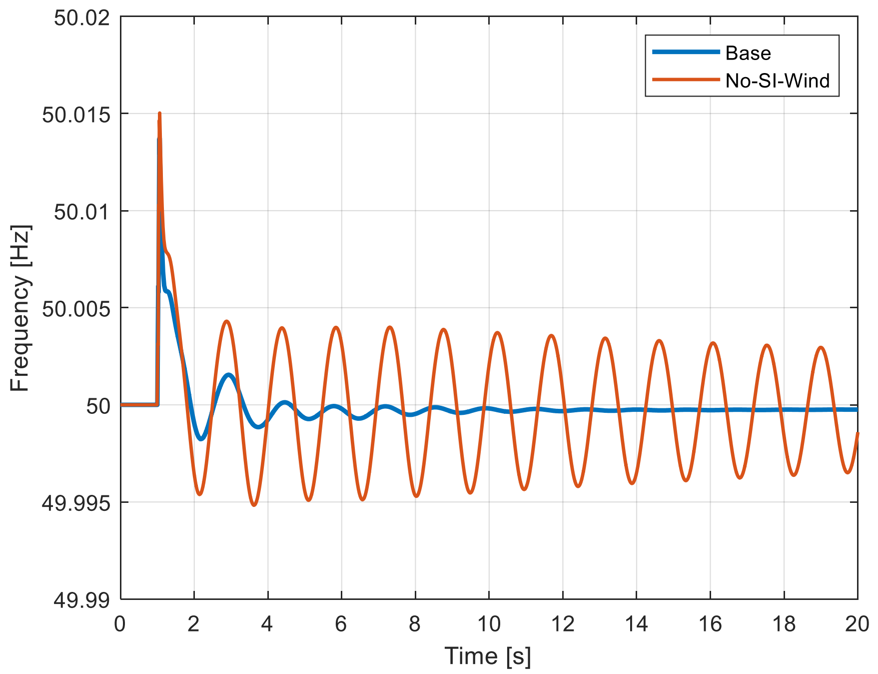

Figure 8. Network: 2030. Dispatching profile: High Export, Event: outage of two of the three connections with continental Italy. Frequency derivative profiles.

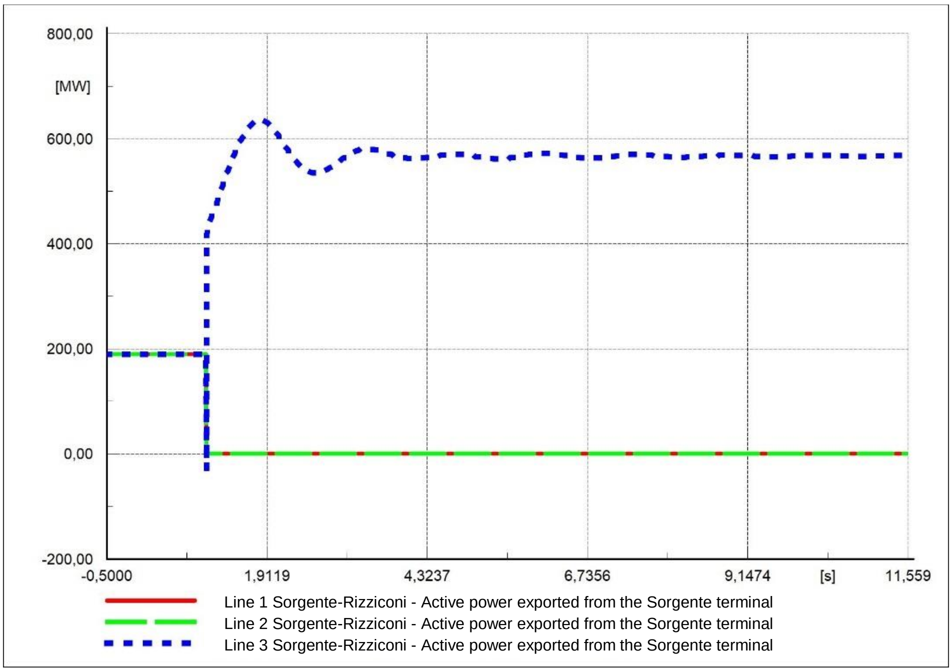

Figure 9. Network: 2030. Dispatching profile: High Export, Event: outage of two of the three connections with continental Italy, base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

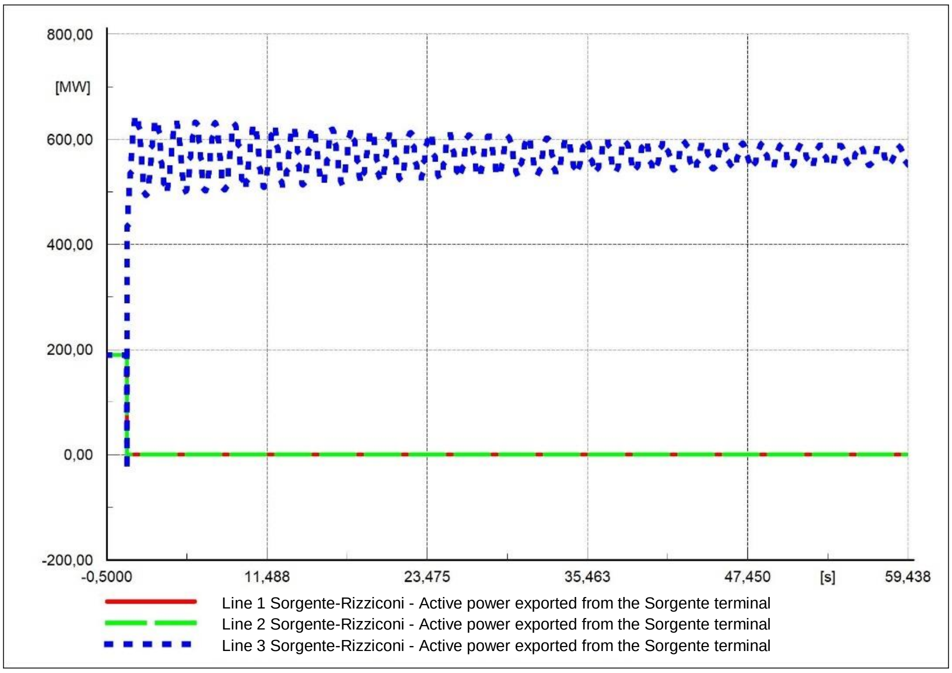

Figure 10. Network: 2030. Dispatching profile: High Export, Event: outage of two of the three connections with continental Italy, No-SI-Wind configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.1.3 Outage of Priolo Power Plant GT1

The following Figure 11 and Figure 12 report the simulation results obtained with the outage of Priolo Power Plant GT1. In this case, the generation loss causes a decrease of frequency. The resulting quasi-steady-state frequency value is slightly lower than 49.98 Hz. The maximal deviation is close to 0.03 Hz both with and without the SI provided by wind generators. In this second case, the maximal deviation and the maximal frequency derivative are slightly higher, but, in any case, frequency stability is guaranteed.

Figure 13 and Figure 14 show the power exchanged through the three connections with continental Italy in the base and No-SI-Wind configurations, respectively. It can be observed that the power export decreases in response to the loss of generation due to the simulated outage.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 0.93 kA.

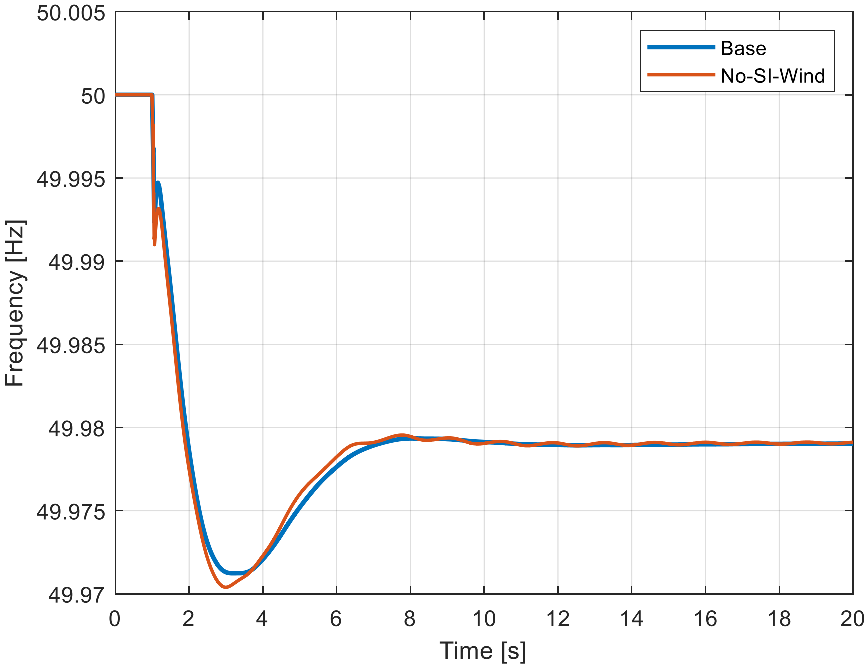

Figure 11. Network: 2030. Dispatching profile: High Export, Event: outage of Priolo Power Plant Module 1 GT (loss of 250 MW of generated power), base configuration. Frequency profiles.

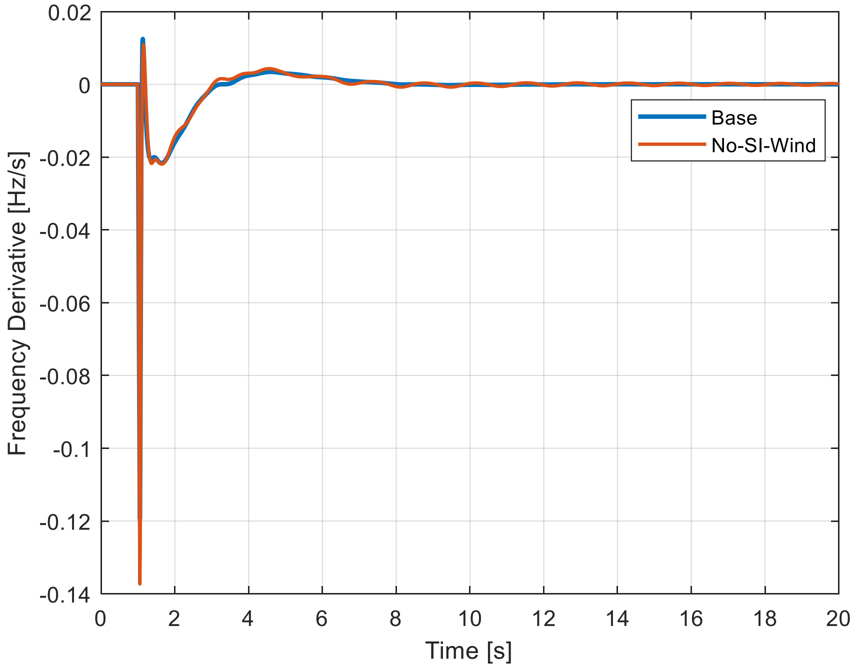

Figure 12. Network: 2030. Dispatching profile: High Export, Event: outage of Priolo Power Plant Module 1 GT (loss of 250 MW of generated power), base configuration. Frequency derivative profiles.

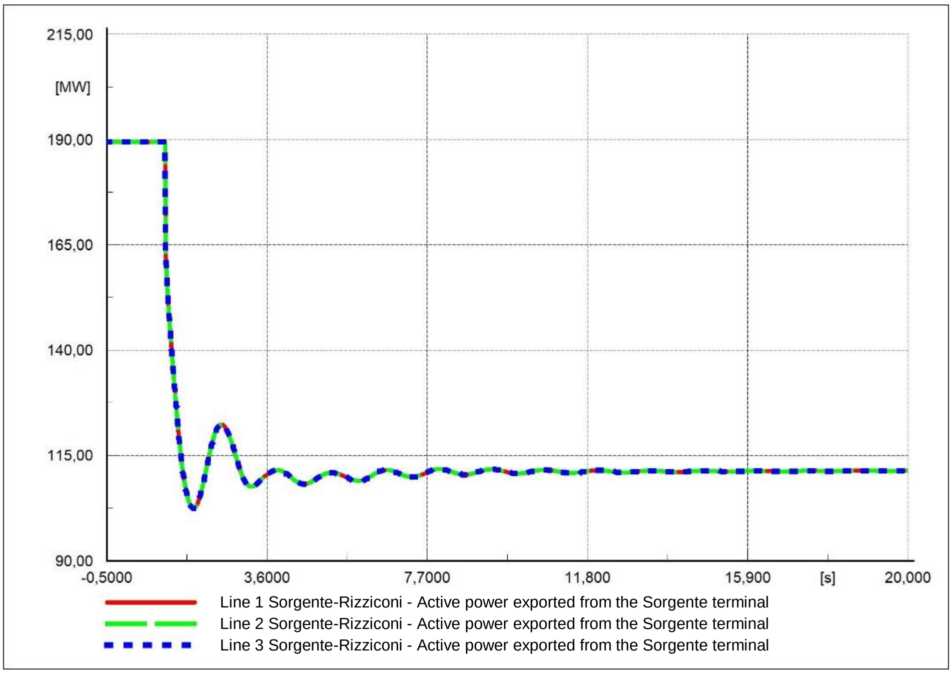

Figure 13. Network: 2030. Dispatching profile: High Export, Event: outage of Priolo Power Plant Module 1 GT (loss of 250 MW of generated power), base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

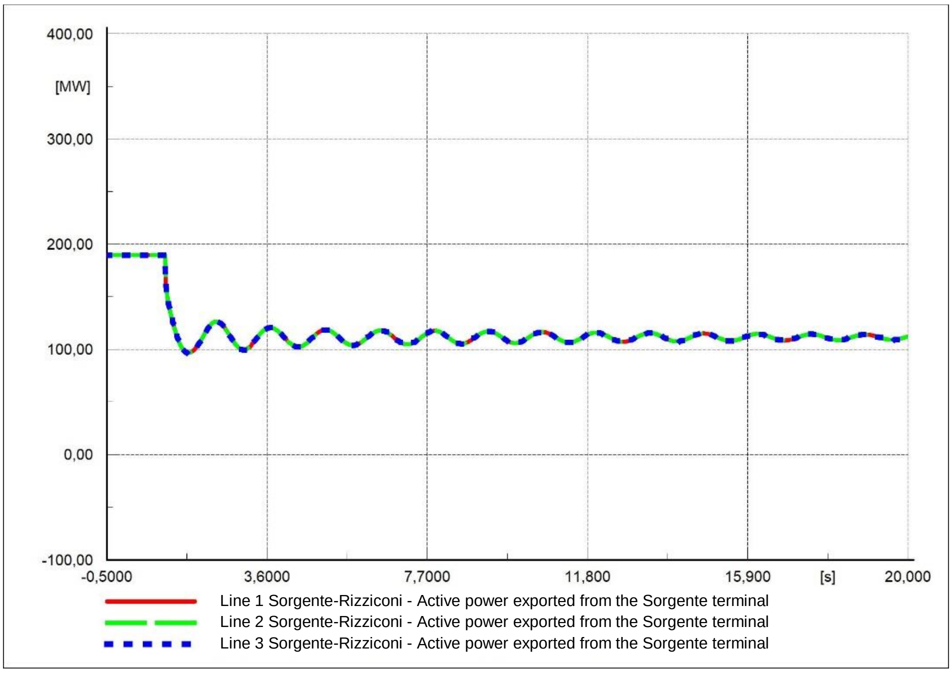

Figure 14. Network: 2030. Dispatching profile: High Export, Event: outage of Priolo Power Plant Module 1 GT (loss of 250 MW of generated power), No-SI-Wind configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.1.4 Outage of Termini Imerese Power Plant CC, GT1 and GT2

The following Figure 15 and Figure 16 report the simulation results obtained with the outage of Termini Imerese Power Plant CC, GT1 and GT2. In this case, the generation loss (815 MW) causes a decrease of frequency. The resulting quasi-steady-state frequency value is around 49.91 Hz. Without the SI provided by wind generators, the maximal frequency deviation and the maximal frequency derivative are slightly higher. In any case, frequency stability is still guaranteed.

Figure 17 and Figure 18 show the power exchanged through the three connections with continental Italy in the base and No-SI-Wind configurations, respectively. It can be observed that the power export decreases and changes sign (import) in response to the large loss of generation caused by the simulated outage.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 0.93 kA.

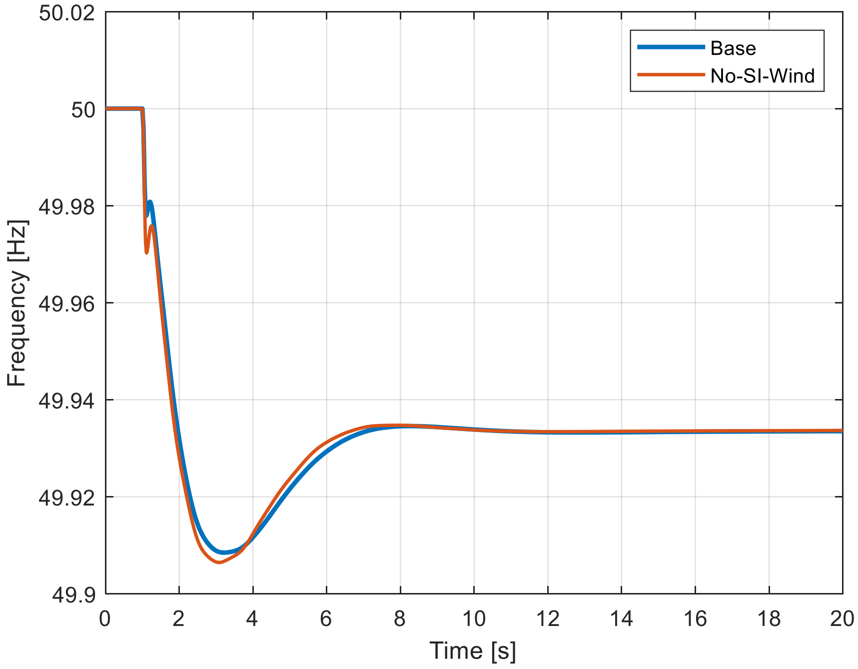

Figure 15. Network: 2030. Dispatching profile: High Export, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 815 MW of generated power), base configuration. Frequency profiles.

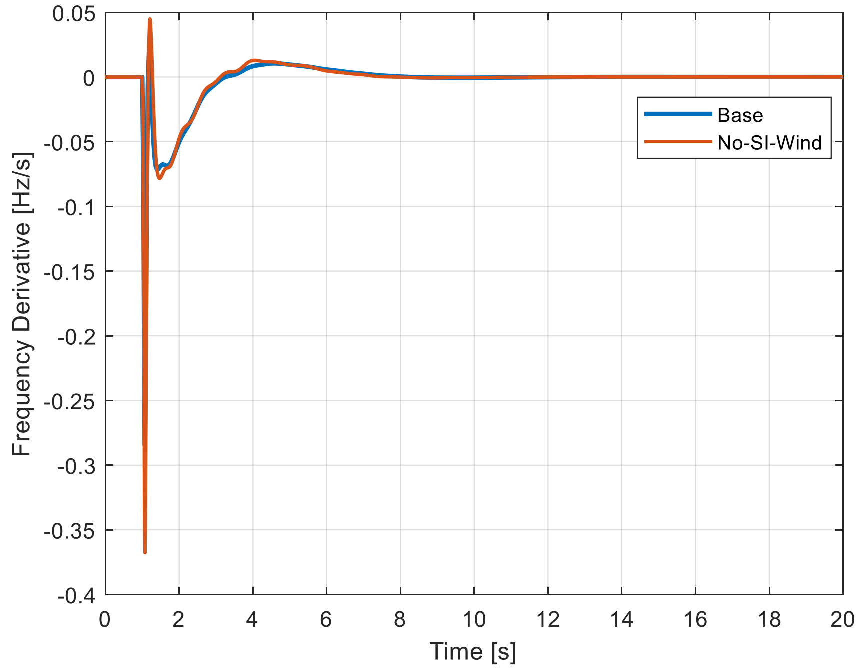

Figure 16. Network: 2030. Dispatching profile: High Export, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 815 MW of generated power), base configuration. Frequency derivative profiles.

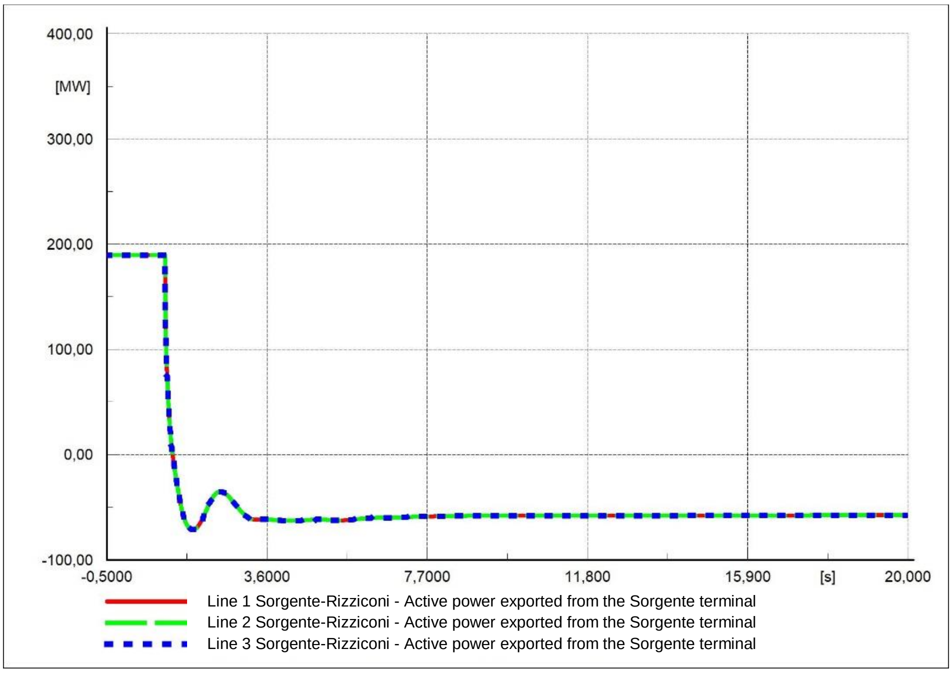

Figure 17. Network: 2030. Dispatching profile: High Export, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 815 MW of generated power), base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

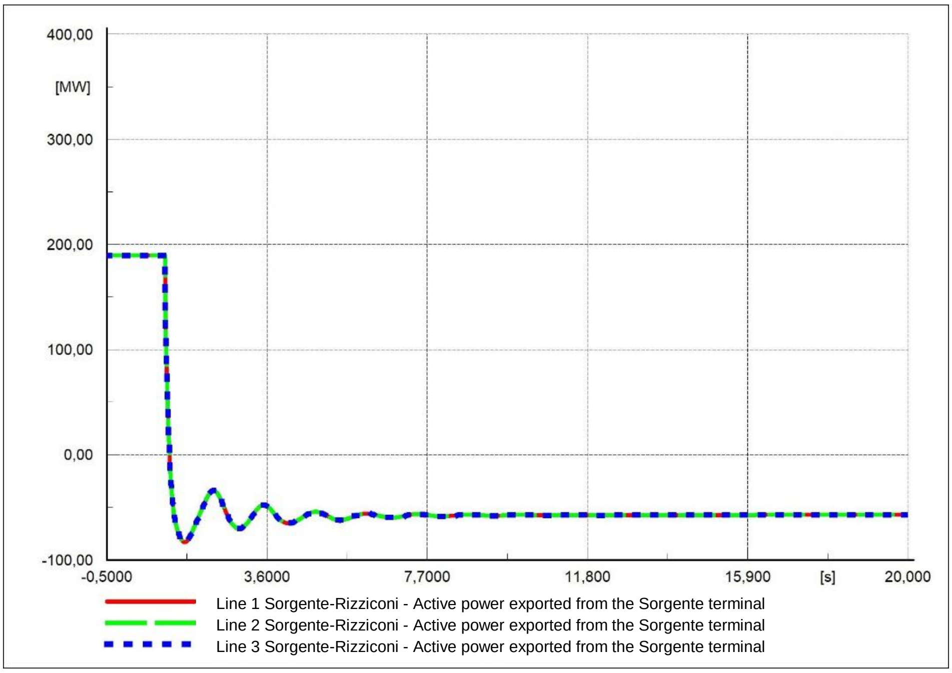

Figure 18. Network: 2030. Dispatching profile: High Export, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 815 MW of generated power), No-SI-Wind configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.2 High Import dispatching profile

In this dispatching profile, the events reported in the following have been simulated:

- outage of one of the three connections with continental Italy;

- outage of two of the three connections with continental Italy;
- outage of Termini Imerese Power Plant CC, GT1 and GT2 (Snom = 946 MVA): loss of 660 MW of generated power.

4.3.1.2.1 Outage of one of the three connections with continental Italy

The following Figure 19 and Figure 20 report the simulation results obtained with the loss of one of the three connections from continental Italy. It can be observed that frequency stability is always guaranteed, also without the SI provided by wind generators.

Figure 21 and Figure 22 show the power exchanged through the three connections with continental Italy in the base and No-SI-Wind configurations, respectively. It can be observed that the power imported by the lost connection is distributed to the two remaining connections.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 0.93 kA.

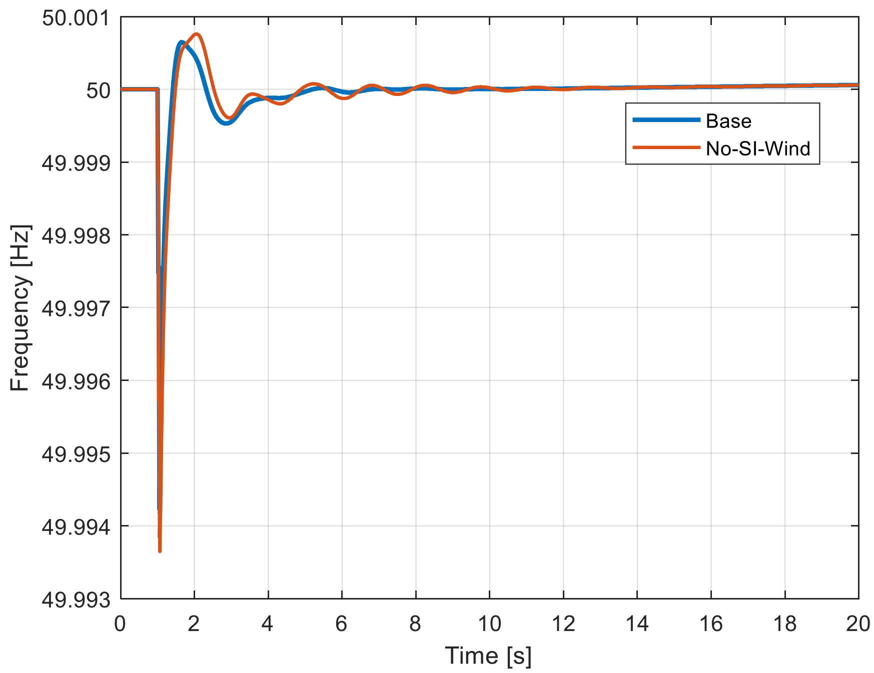

Figure 19. Network: 2030. Dispatching profile: High Import, Event: outage of one of the three connections with continental Italy. Frequency profiles.

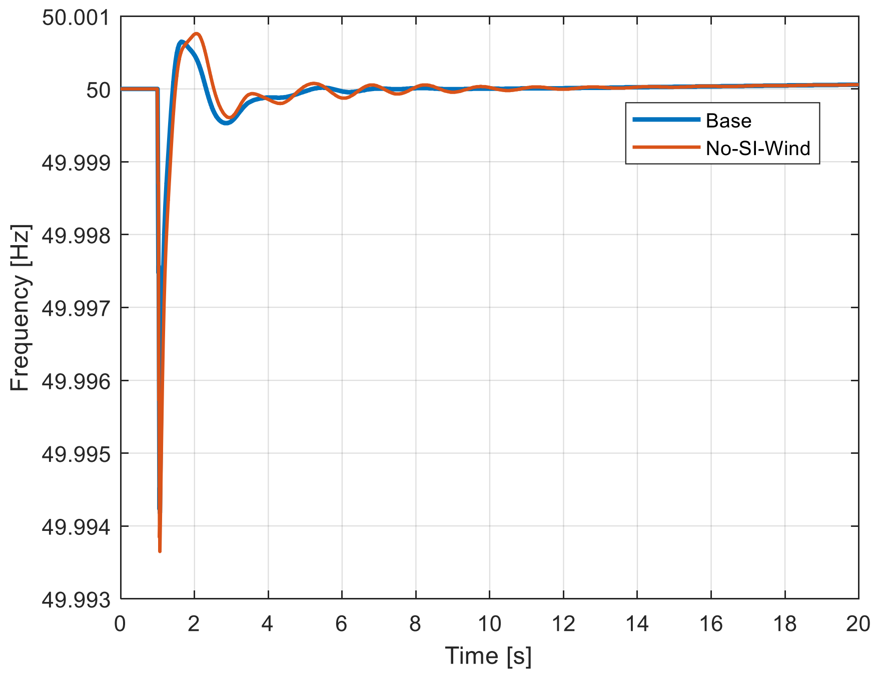

Figure 20. Network: 2030. Dispatching profile: High Import, Event: outage of one of the three connections with continental Italy. Frequency derivative profiles.

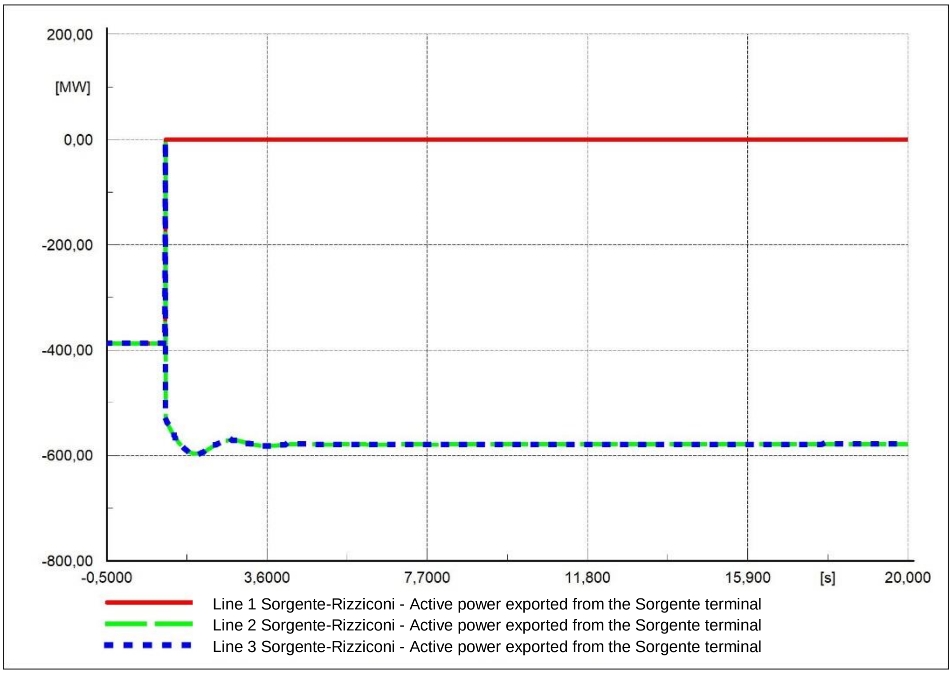

Figure 21. Network: 2030. Dispatching profile: High Import, Event: outage of one of the three connections with continental Italy, base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

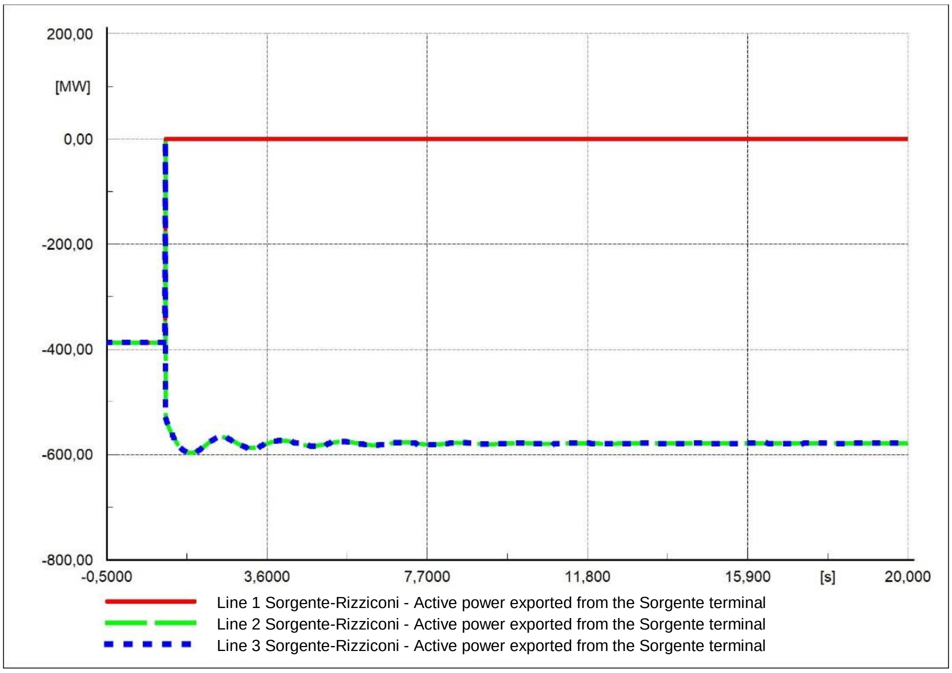

Figure 22. Network: 2030. Dispatching profile: High Import, Event: outage of one of the three connections with continental Italy, No-SI-Wind configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.2.2 Outage of two of the three connections with continental Italy

In this subsection, we present the results of a stress test we carried out to check when flexibility resources can become necessary for the stability of the Sicily network. The situation studied is just an academic exercise very unlikely to occur during the actual operation of the network. The following figures from Figure 23 to Figure 25 show the results obtained with the outage of two out of the three connections with continental Italy. 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.

As shown in Figure 23, the loss of 1100 MW of imported power determines a severe decrease of frequency. In the base configuration (blue line), frequency reaches a minimum value of 48.8 Hz. During the decrease, the two first steps of load shedding (9 and 8 %) are activated. Indeed, referring to Table 1, after the frequency has crossed the thresholds of 49.3 Hz and 49.2 Hz, the frequency derivative threshold of -0.6 Hz/s is violated. Frequency derivative is shown in Figure 24, where a zoom of the two first seconds after the event is reported. Since at 48.8 Hz the third level of load shedding is activated (7 %), in the base configuration there is a total shedding of the 24 % of the total load, which corresponds to 738 MW. Thanks to such a decrease of load, frequency recovers toward the nominal value reaching a quasi-steady-state value slightly higher than 49.4 Hz.

Without the SI provided by wind generators, the frequency decrease is faster, with a higher derivative, which provokes, in a couple of seconds, the shedding of all the four levels of load, *i.e.,* the 31 % of the total load, corresponding to 953 MW. This huge decrease of load allows frequency to increase toward a quasi-steady-state value higher than 49.8 Hz.

To avoid or reduce the load shedding, three levels of DSR, FCR, reported in Table 9, have been considered.

Network Configuration	K_{DSR}^{tot} [MW]	% DSR	% Loads Operating 5 % DSR	% Loads Operating 10 % DSR
DSR-25	155	5 %	101 %	50 %
DSR-50	310	10 %	201 %	101 %
DSR-70	434	14 %	282 %	141 %

*Total Load = 3075 MW

Table 9. Network 2030. DSR FCR network configuration parameters for dispatching profile "High-Import".

The FCR provided in the three cases (DSR-25, DSR-50, DSR-70) are 155 MW, 310 MW and 434 MW, respectively. The frequency derivative and the frequency maximal deviation are progressively reduced. In particular, in the DSR-25 case, frequency does not reach the threshold of 48.8 Hz and only the first (9 %) and second (8 %) levels of load shedding are activated for a total of 523 MW. The larger FCRs used in the DSR-50 and DSR-75 cases further reduce the maximal frequency deviation, but load shedding is not reduced.

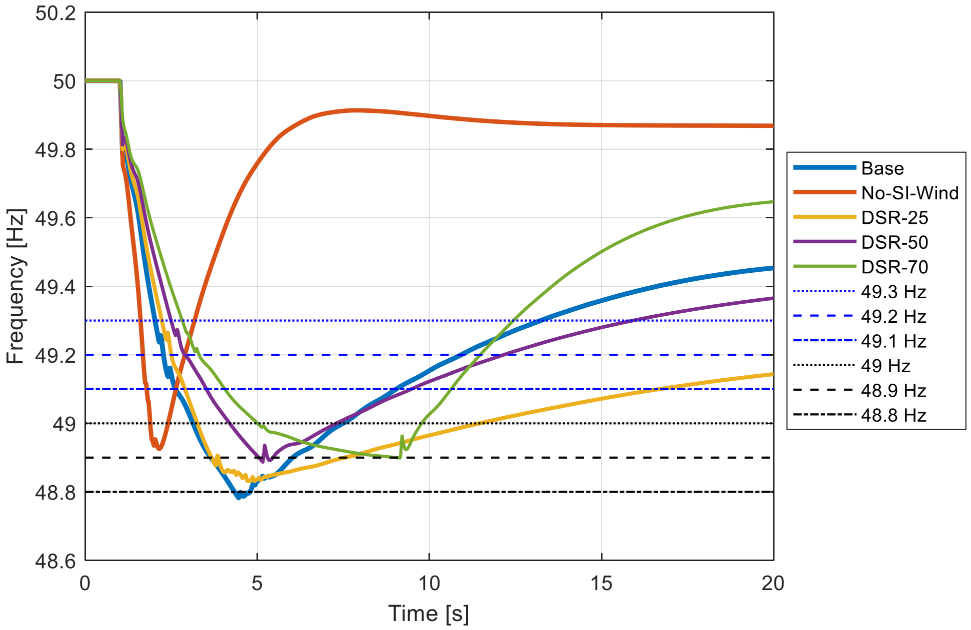

Figure 23. Network: 2030. Dispatching profile: High Import, Event: outage of two of the three connections with continental Italy. Frequency profiles.

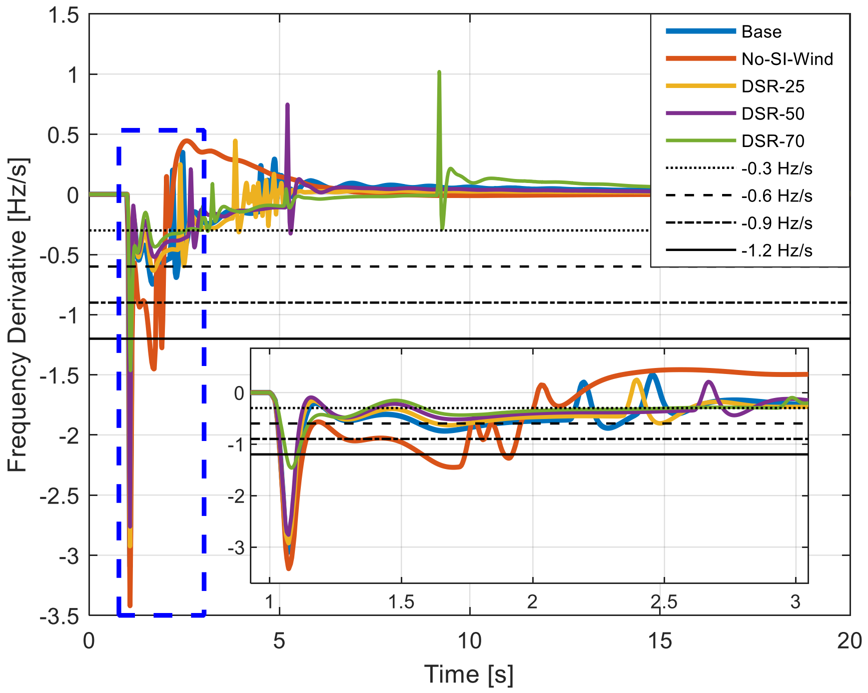

Figure 24. Network: 2030. Dispatching profile: High Import, Event: outage of two of the three connections with continental Italy. Frequency derivative profiles.

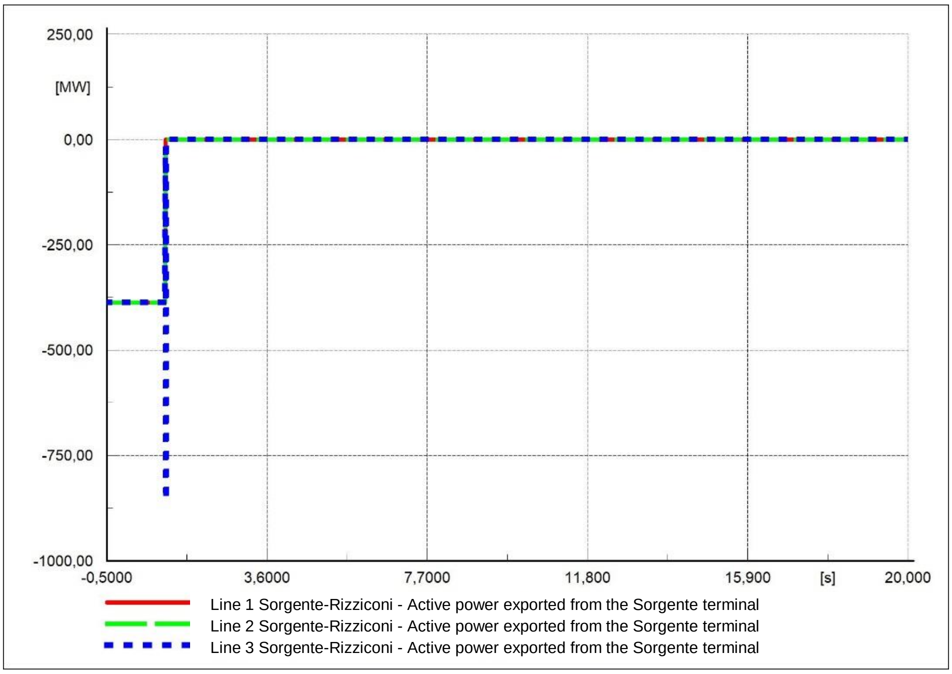

Figure 25. Network: 2030. Dispatching profile: High Import, Event: outage of two of the three connections with continental Italy, base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.2.3 Outage of Termini Imerese Power Plant CC, GT1 and GT2

The following Figure 26 and Figure 27 report the simulation results obtained with the outage of Termini Imerese Power Plant CC, GT1 and GT2. In this case, the generation loss (660 MW) causes a decrease of frequency. The resulting quasi-steady-state frequency value is around

49.965 Hz. Without the SI provided by wind generators, the maximal frequency deviation and the maximal frequency derivative are slightly higher. In any case, frequency stability is guaranteed.

Figure 28 and Figure 29 show the power exchanged through the three connections with continental Italy in the base and No-SI-Wind configurations, respectively. It can be observed that the power import increases (in the figures, the negative value indicates power import) in response to the large loss of generation caused by the simulated outage.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 0.93 kA.

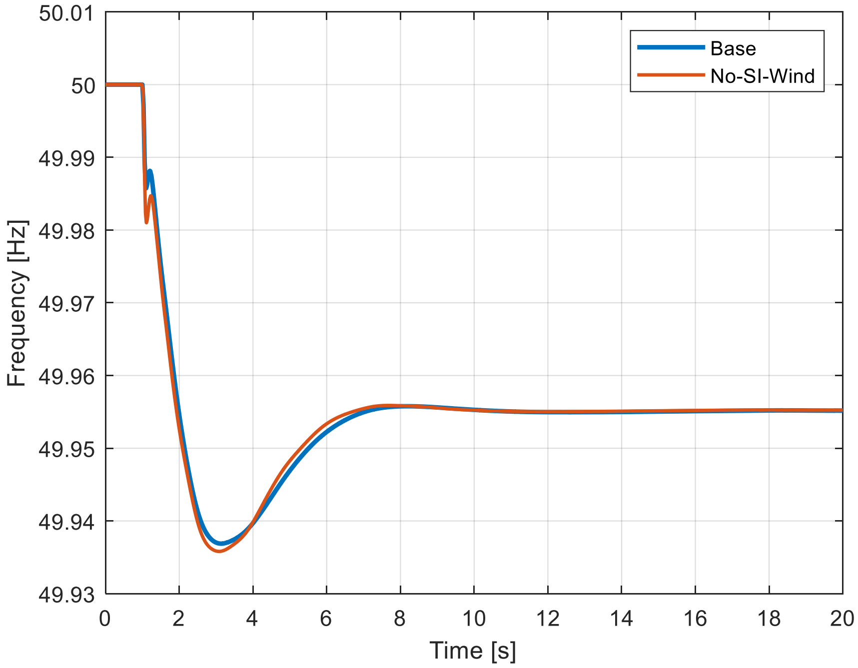

Figure 26. Network: 2030. Dispatching profile: High Import, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 660 MW of generated power), base configuration. Frequency profiles.

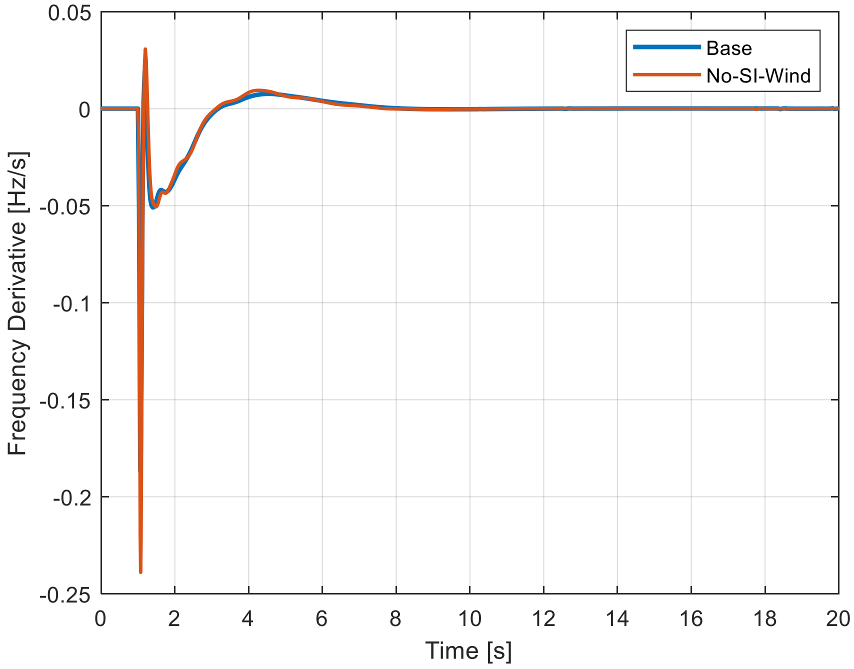

Figure 27. Network: 2030. Dispatching profile: High Import, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 660 MW of generated power), base configuration. Frequency derivative profiles.

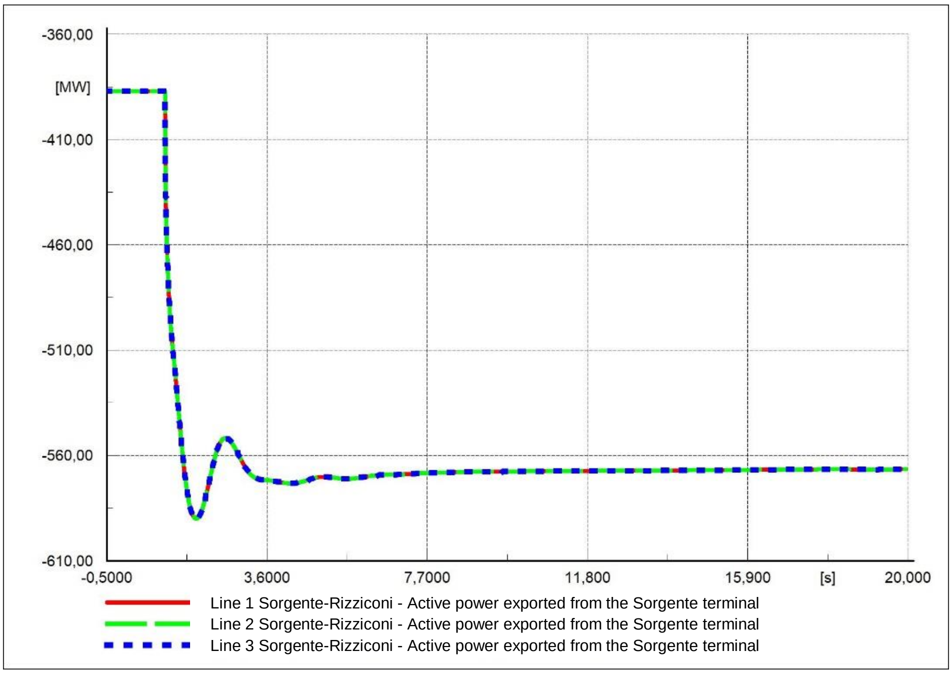

Figure 28. Network: 2030. Dispatching profile: High Import, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 660 MW of generated power), base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

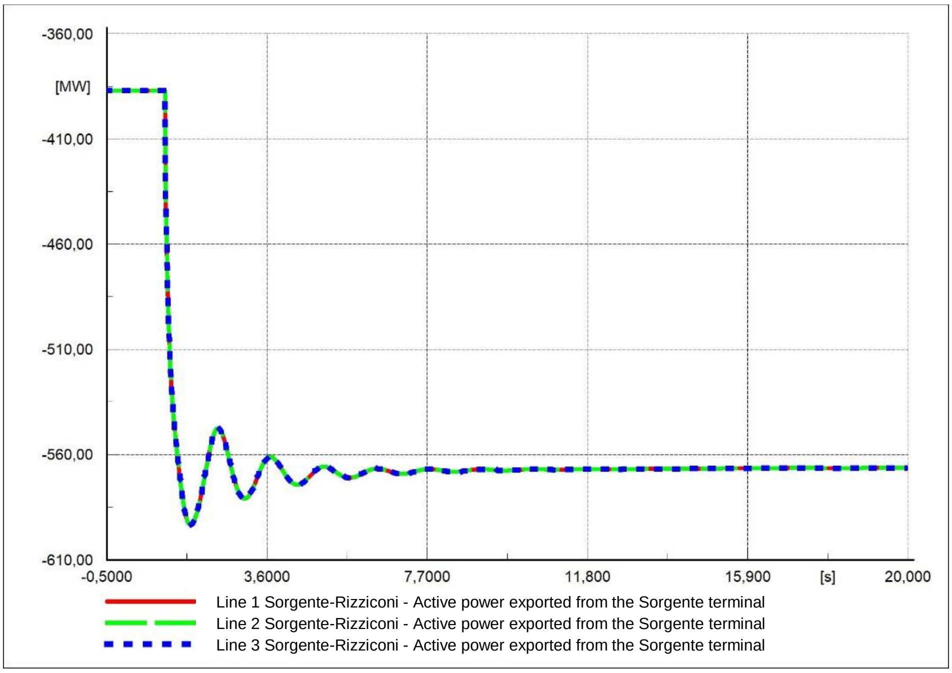

Figure 29. Network: 2030. Dispatching profile: High Import, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 660 MW of generated power), No-SI-Wind configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.3 High Load / Low Gas dispatching profile

In this dispatching profile, the events reported in the following have been simulated:

- outage of one of the three connections with continental Italy;
- outage of two of the three connections with continental Italy;
- outage of Termini Imerese Power Plant CC, GT1 and GT2 (Snom = 946 MVA): loss of 337 MW of generated power.

No DSR FCR network configuration has been here considered, since frequency stability is guaranteed by the base configuration.

4.3.1.3.1 Outage of one of the three connections with continental Italy

The following Figure 30 and Figure 31 report the simulation results obtained with the loss of one of the three connections from continental Italy. It can be observed that frequency stability is always guaranteed, also without the SI operated by wind generators. Indeed, the frequency deviation is lower than 2 mHz in both configuration cases.

Figure 32 and Figure 33 show the power exchanged through the three connections with continental Italy in the base and No-SI-Wind configurations, respectively. It can be observed that the power exported by the lost connection is distributed to the two remaining connections.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 0.93 kA.

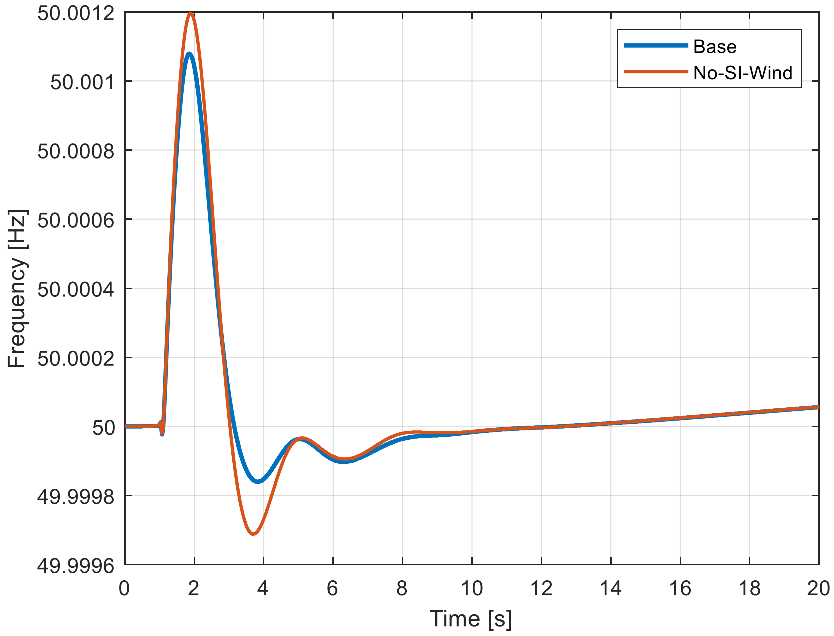

Figure 30. Network: 2030. Dispatching profile: High Load / Low Gas, Event: outage of one of the three connections with continental Italy. Frequency profiles.

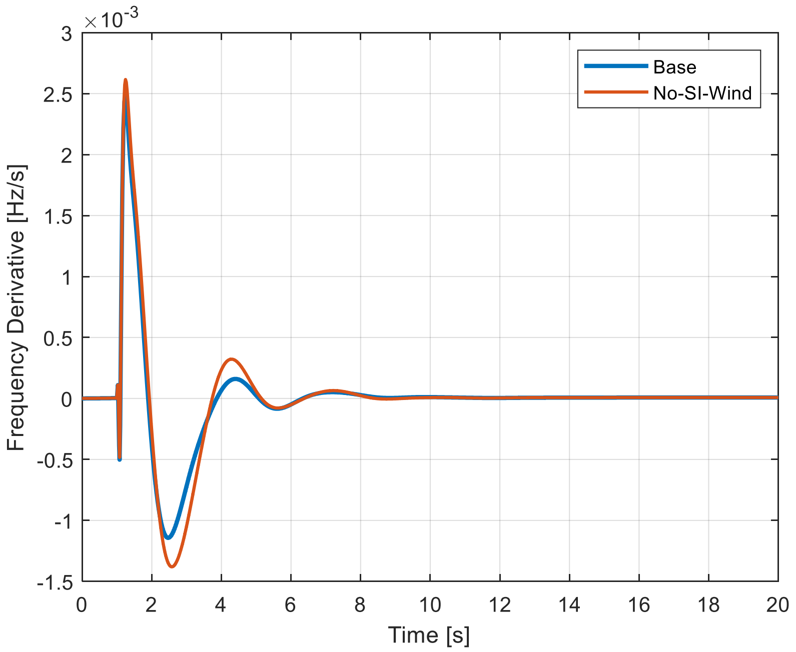

Figure 31. Network: 2030. Dispatching profile: High Load / Low Gas, Event: outage of one of the three connections with continental Italy. Frequency derivative profiles.

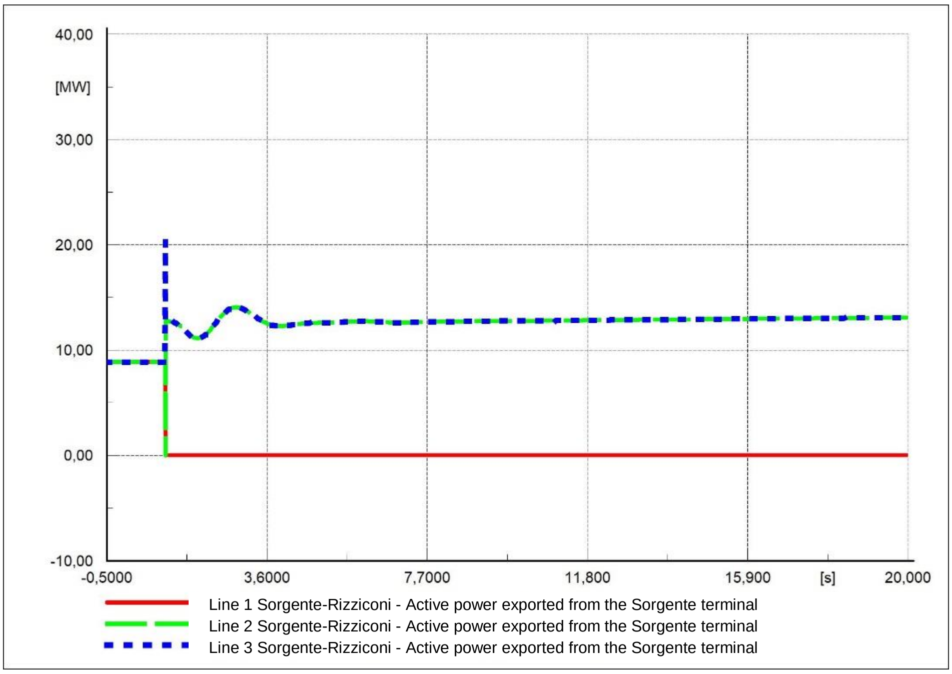

Figure 32. Network: 2030. Dispatching profile: High Load / Low Gas, Event: outage of one of the three connections with continental Italy, base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

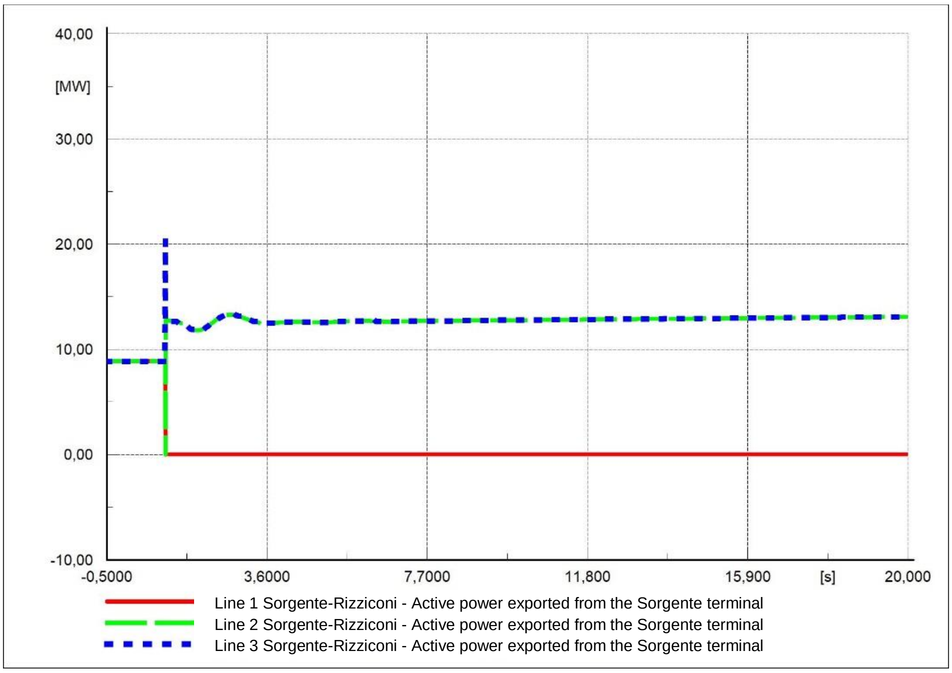

Figure 33. Network: 2030. Dispatching profile: High Load / Low Gas, Event: outage of one of the three connections with continental Italy, No-SI-Wind configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.3.2 Outage of two of the three connections with continental Italy

The following Figure 34 and Figure 35 report the simulation results obtained with loss of two of the connection with continental Italy. In this case, frequency stability is guaranteed both with and without the SI provided by wind generators, with a maximal deviation of about 2 mHz.

Figure 36 and Figure 37 show the power exchanged through the three connections with continental Italy in the base and No-SI-Wind configurations, respectively. It can be observed that the power exported by the lost connections is entirely exported by the third one.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 0.93 kA.

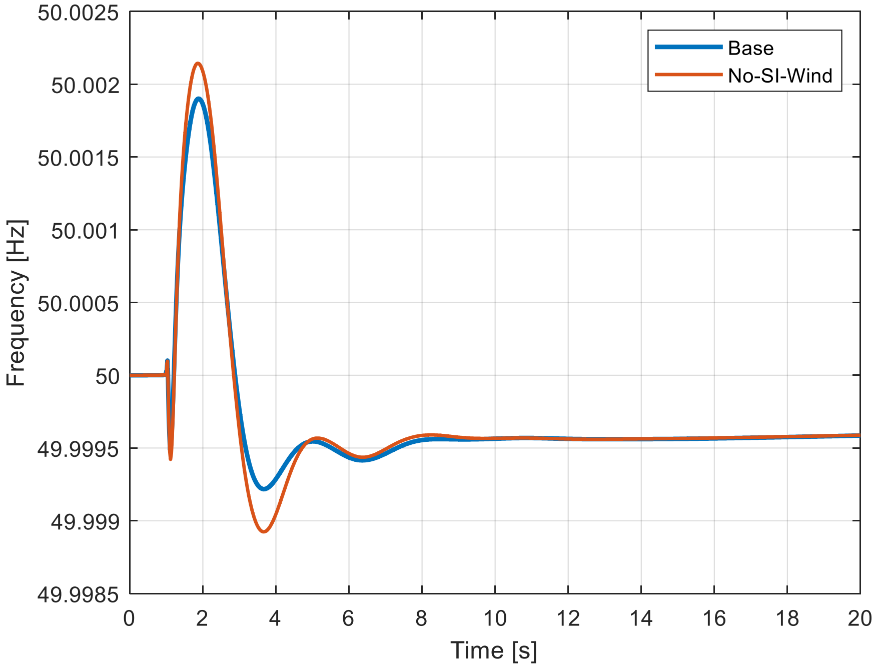

Figure 34. Network: 2030. Dispatching profile: High Load / Low Gas, Event: outage of two of the three connections with continental Italy. Frequency profiles.

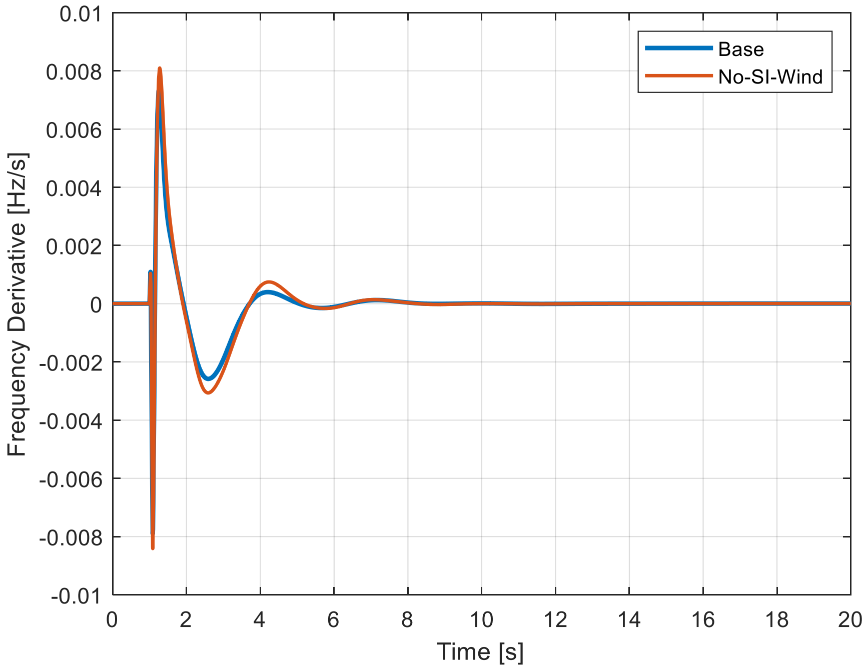

Figure 35. Network: 2030. Dispatching profile: High Load / Low Gas, Event: outage of two of the three connections with continental Italy. Frequency derivative profiles.

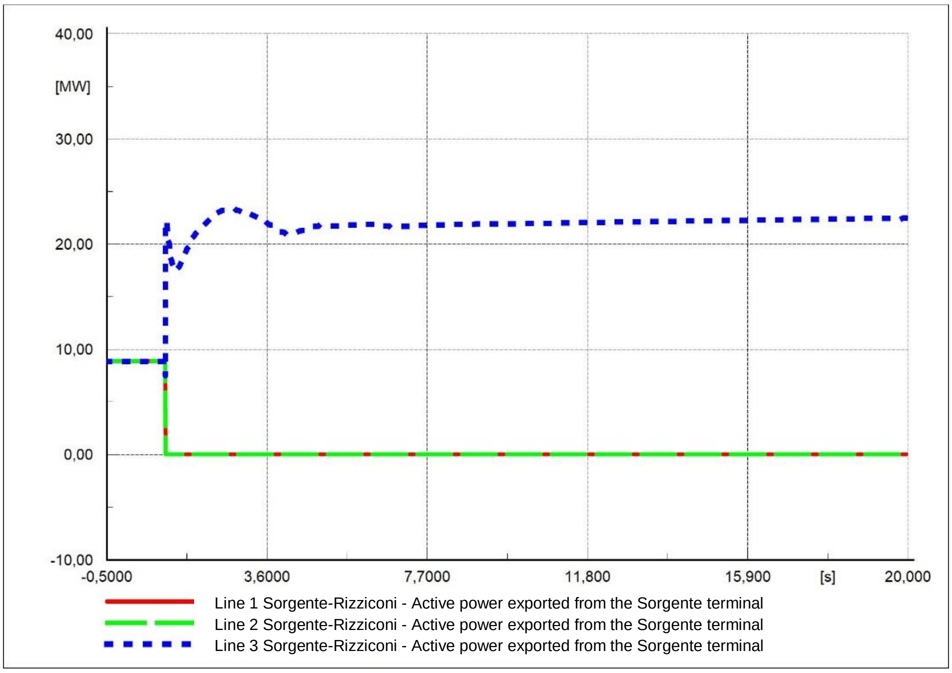

Figure 36. Network: 2030. Dispatching profile: High Load / Low Gas, Event: outage of two of the three connections with continental Italy, base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

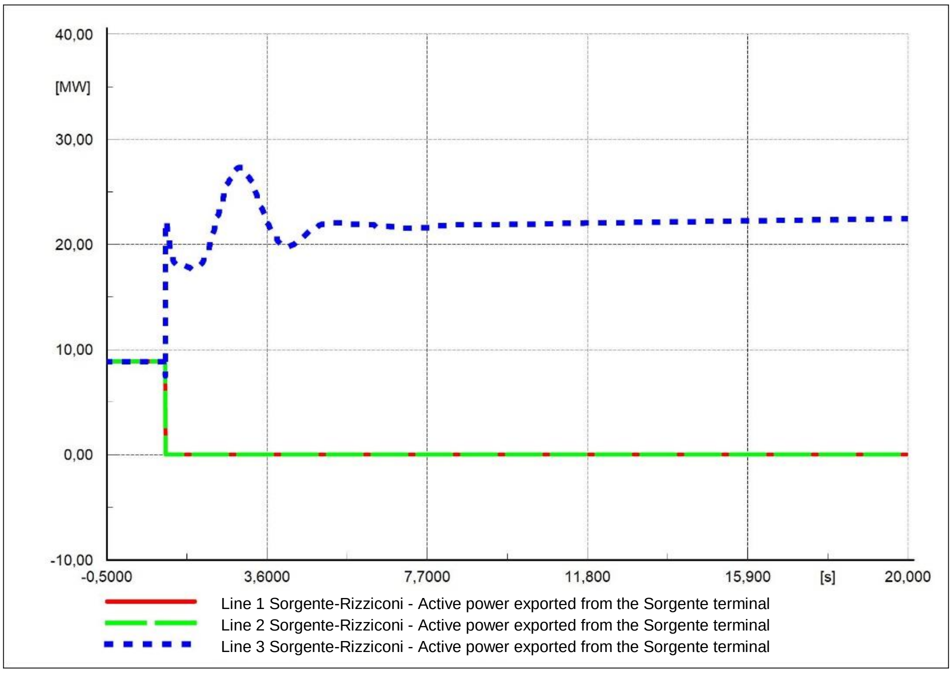

Figure 37. Network: 2030. Dispatching profile: High Load / Low Gas, Event: outage of two of the three connections with continental Italy, No-SI-Wind configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.3.3 Outage of Termini Imerese Power Plant CC, GT1 and GT2

The following Figure 38 and Figure 39 report the simulation results obtained with the outage of Termini Imerese Power Plant CC, GT1 and GT2. In this case, the generation loss (337 MW) causes a decrease of frequency. The resulting quasi-steady-state frequency value is around

49.953 Hz. Without the SI provided by wind generators, the maximal frequency deviation and the maximal frequency derivative are slightly higher. In any case, frequency stability is guaranteed.

Figure 40 and Figure 41 show the power exchanged through the three connections with continental Italy in the base and No-SI-Wind configurations, respectively. It can be observed that the power import increase (in the figures a negative value indicates power import) in response to the large loss of generation caused by the simulated outage.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 0.93 kA.

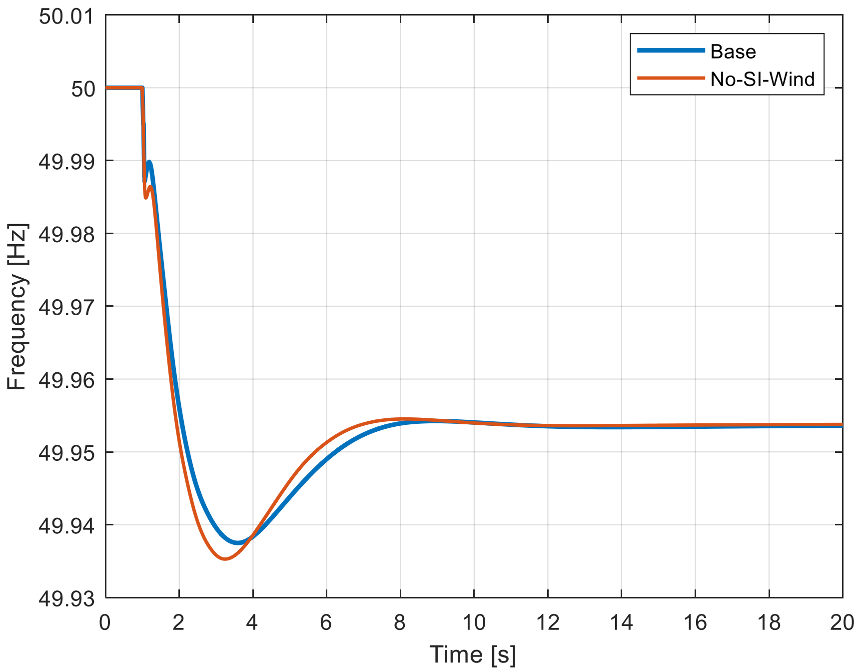

Figure 38. Network: 2030. Dispatching profile: High Load / Low Gas, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 337 MW of generated power), base configuration. Frequency profiles.

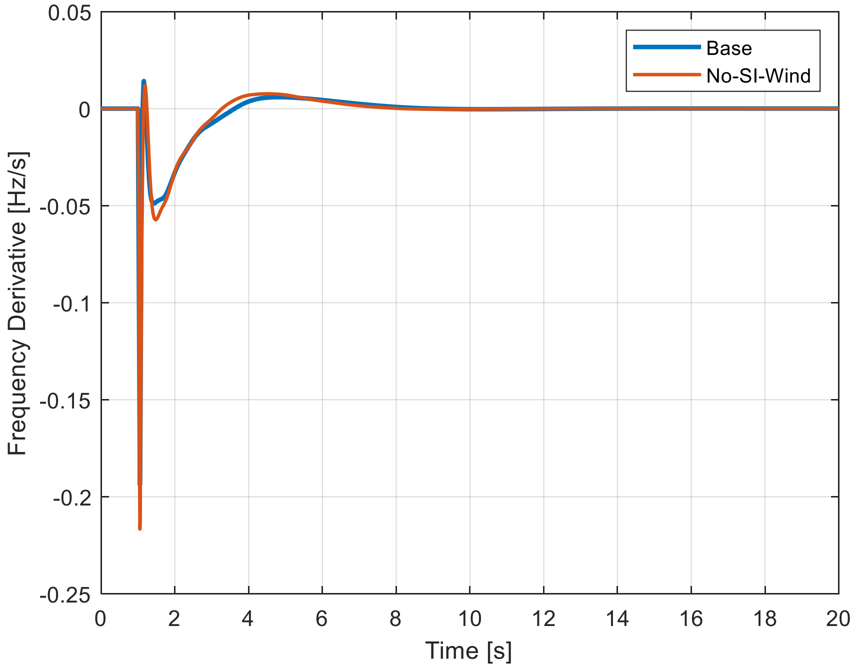

Figure 39. Network: 2030. Dispatching profile: High Load / Low Gas, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 337 MW of generated power), base configuration. Frequency derivative profiles.

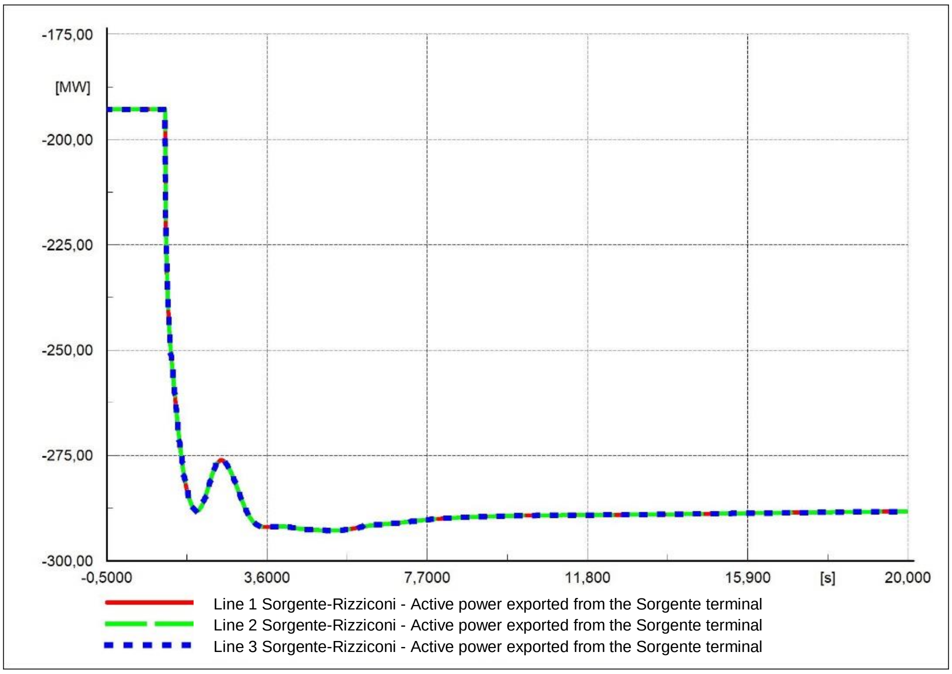

Figure 40. Network: 2030. Dispatching profile: High Export, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 337 MW of generated power), base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

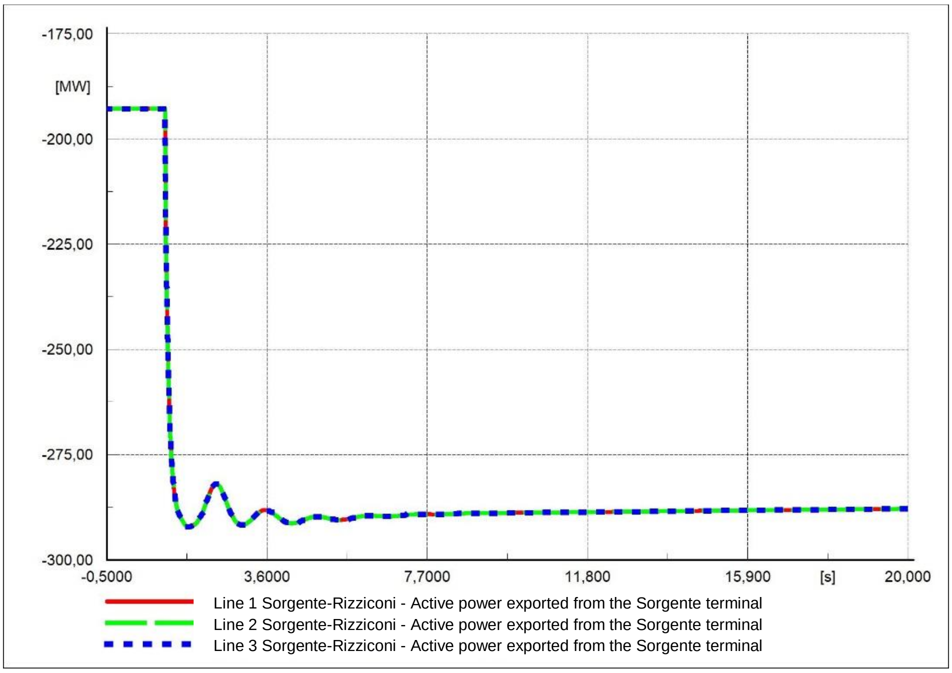

Figure 41. Network: 2030. Dispatching profile: High Load / Low Gas, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 337 MW of generated power), No-SI-Wind configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.4 Island dispatching profile

In this dispatching profile, the events reported in the following have been simulated:

- outage of Termini Imerese Power Plant GT1 (Snom = 288 MVA): loss of 127 MW of generated power;
- outage of Termini Imerese Power Plant CC, GT1 (Snom = 658 MVA): loss of 210 MW of generated power.

4.3.1.4.1 Outage of Termini Imerese Power Plant GT1

The following Figure 42 and Figure 43 report the simulation results obtained with the outage of Termini Imerese Power Plant GT1. In this case, both with and without SI operated by wind generators, frequency is controlled with a maximum deviation of about 0.28 Hz.

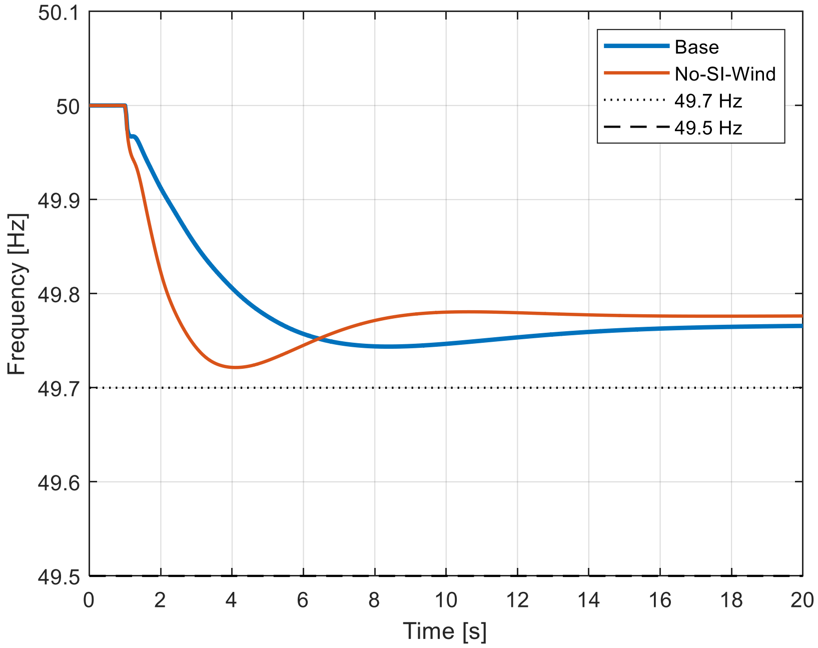

Figure 42. Network: 2030. Dispatching profile: Island, Event: outage of Termini Imerese Power Plant GT1 (loss of 127 MW of generated power). Frequency profiles.

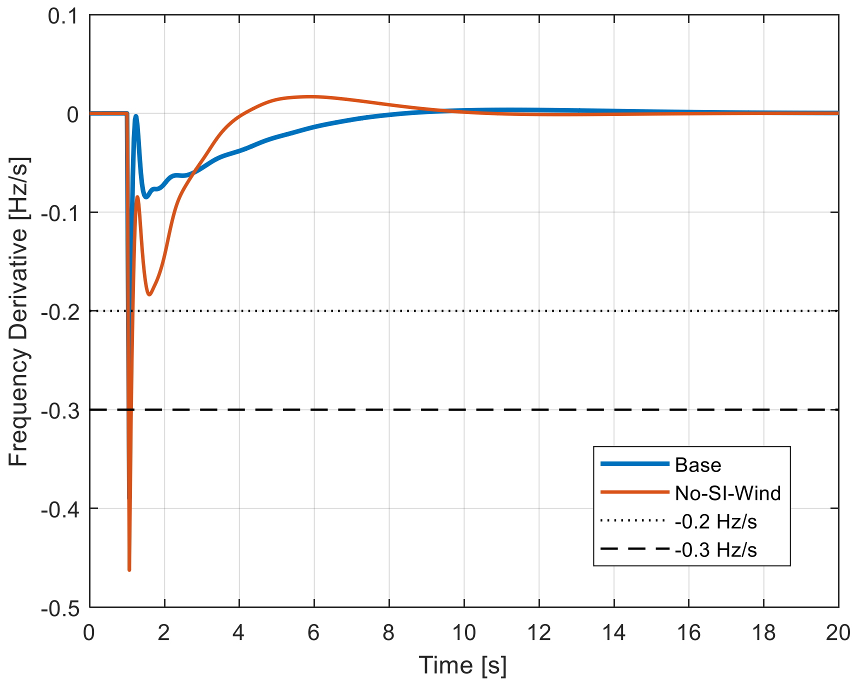

Figure 43. Network: 2030. Dispatching profile: Island, Event: outage of Termini Imerese Power Plant GT1 (loss of 127 MW of generated power). Frequency derivative profiles.

4.3.1.4.2 Outage of Termini Imerese Power Plant CC and GT1

Figure 44 and Figure 45 how the simulation results obtained with the outage of Termini Imerese Power Plant Combined Cycle (CC) and GT1. In this case, a severe frequency decrease occurs.

Both with and without the SI provided by wind generators, the threshold of 48.8 Hz is reached, provoking the shedding of the 24 % of the total load, which corresponds to 707 MW. Because of load shedding, frequency increases and reaches a quasi-steady-state value of around 50.5 Hz with the SI provided by wind generators, and of around 50.6 Hz in the base configuration.

In order to avoid load shedding, the DSR FCR network configurations listed in Table 10 have been considered:

Network Configuration	K_{DSR}^{tot} [MW]	% DSR	% Loads Operating 5 % DSR	% Loads Operating 10 % DSR
DSR-10	62	2 %	42 %	21 %
DSR-20	124	4 %	84 %	42 %

*Total Load = 2944 MW

Table 10. Network 2030. DSR FCR network configuration parameters for dispatching profile Island.

With a DSR FCR of 62 MW (DSR - 10) load shedding is only delayed. With a DSR FCR of 124 MW (DSR - 20), load shedding is avoided by keeping frequency higher than 49.7 Hz.

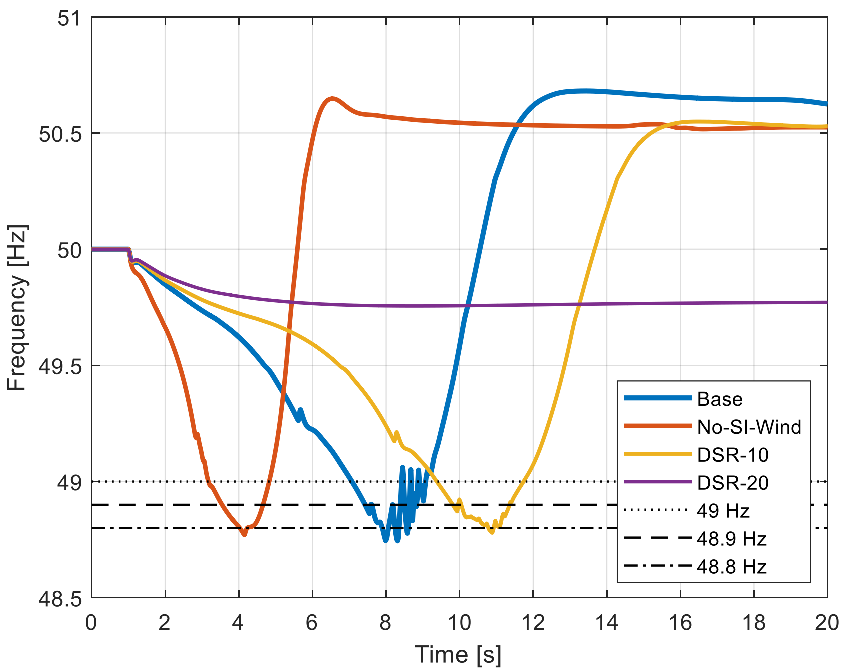

Figure 44. Network: 2030. Dispatching profile: Island, Event: outage of Termini Imerese Power Plant CC and GT1 (loss of 210 MW of generated power). Frequency profiles.

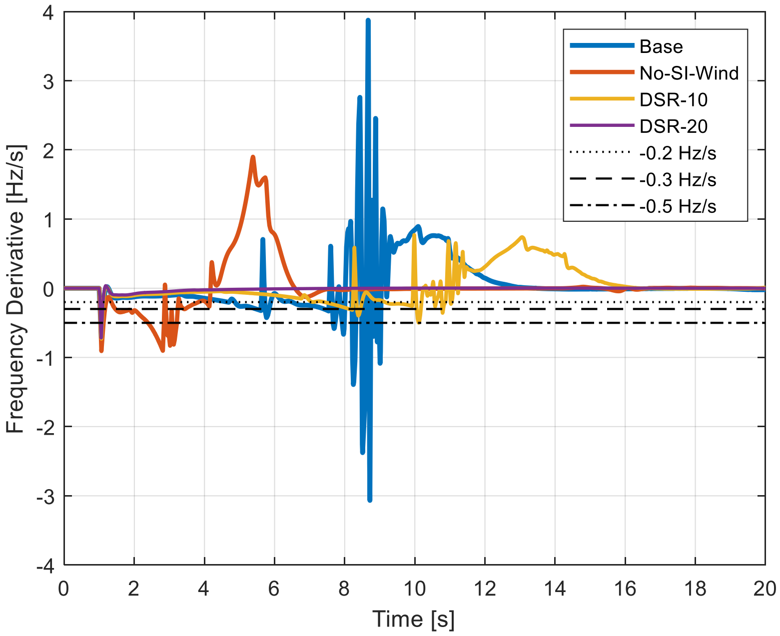

Figure 45. Network: 2030. Dispatching profile: Island, Event: outage of Termini Imerese Power Plant CC and GT1 (loss of 210 MW of generated power). Frequency derivative profiles.

4.3.1.5 Low Load / Low Gas dispatching profile

In this dispatching profile, the events reported in the following have been simulated:

- outage of one of the three connections with continental Italy;
- outage of two of the three connections with continental Italy;
- outage of Termini Imerese Power Plant CC, GT1 and GT2 (Snom = 946 MVA): loss of 337 MW of generated power.

No DSR FCR network configuration has been here considered, since frequency stability is guaranteed by the base configuration.

4.3.1.5.1 Outage of one of the three connections with continental Italy

The following Figure 46 and Figure 47 report the simulation results obtained with the loss of one of the three connections from continental Italy. It can be observed that frequency stability is always guaranteed, also without the SI operated by wind generators.

Figure 48 and Figure 49 show the power exchanged through the three connections with continental Italy in the base and No-SI-Wind configurations, respectively. It can be observed that the power imported by the lost connection is distributed to the two remaining connections.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 0.93 kA.

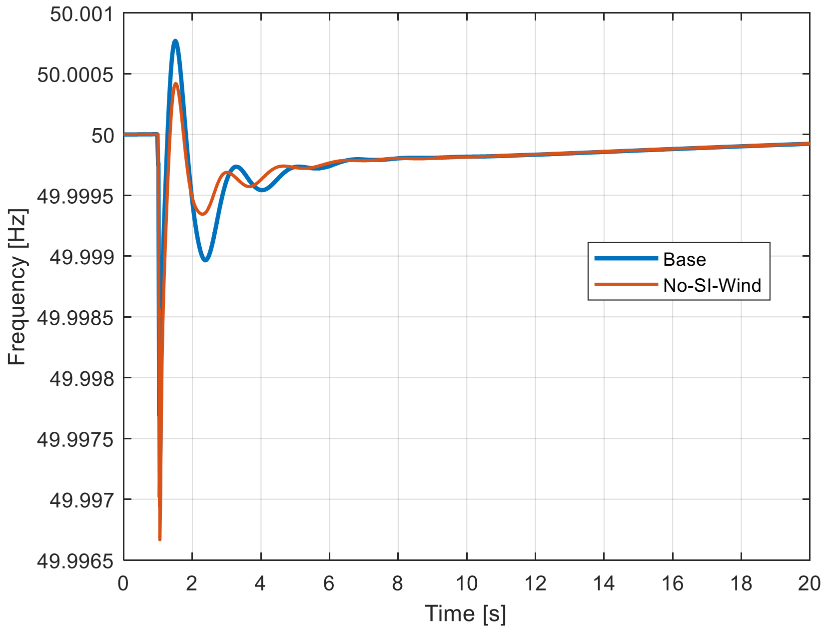

Figure 46. Network: 2030. Dispatching profile: Low Load / Low Gas, Event: outage of one of the three connections with continental Italy. Frequency profiles.

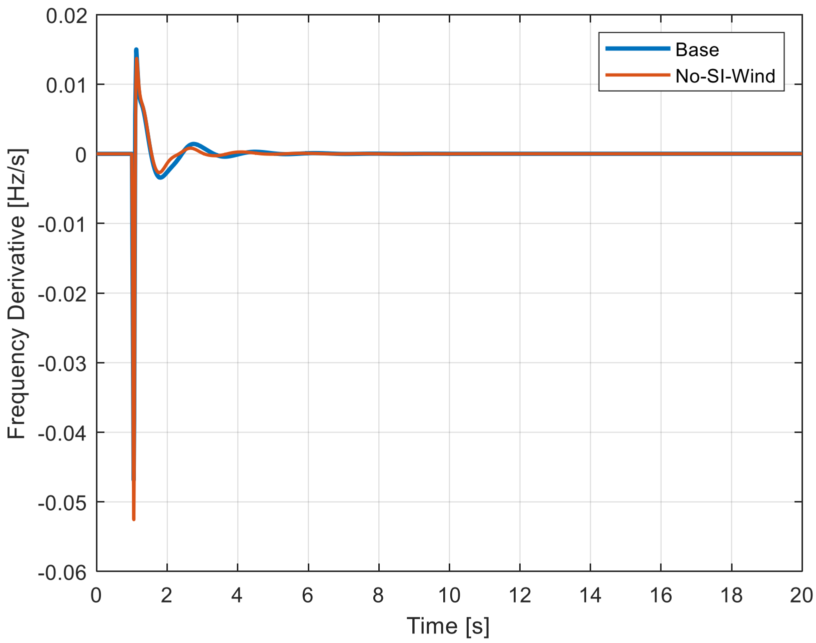

Figure 47. Network: 2030. Dispatching profile: Low Load / Low Gas, Event: outage of one of the three connections with continental Italy. Frequency derivative profiles.

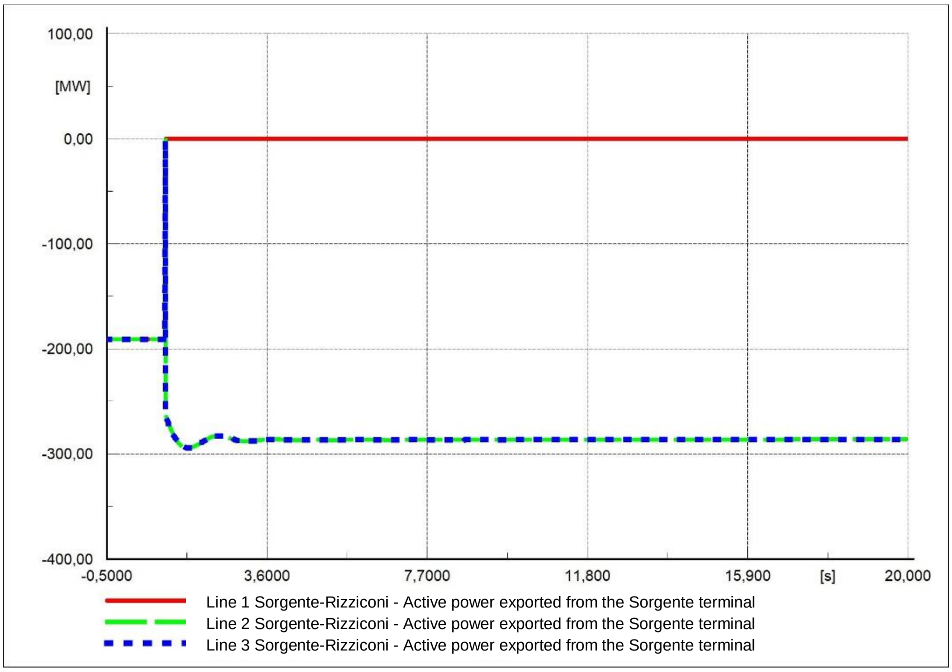

Figure 48. Network: 2030. Dispatching profile: Low Load / Low Gas, Event: outage of one of the three connections with continental Italy, base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

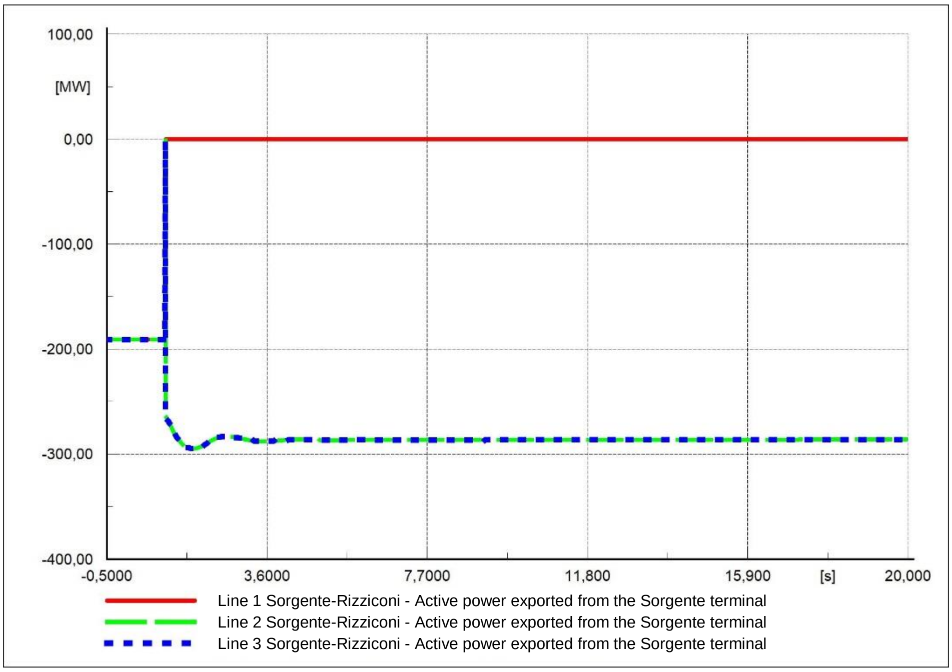

Figure 49. Network: 2030. Dispatching profile: Low Load / Low Gas, Event: outage of one of the three connections with continental Italy, No-SI-Wind configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.5.2 Outage of two of the three connections with continental Italy

The following Figure 50 and Figure 51 report the simulation results obtained with loss of two of the connection with continental Italy. In this case, frequency stability is guaranteed both with and without the SI provided by wind generators.

Figure 52 and Figure 53 show the power exchanged through the three connections with continental Italy in the base and No-SI-Wind configurations, respectively. It can be observed that the power imported by the lost connections is entirely imported by third one.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 0.93 kA.

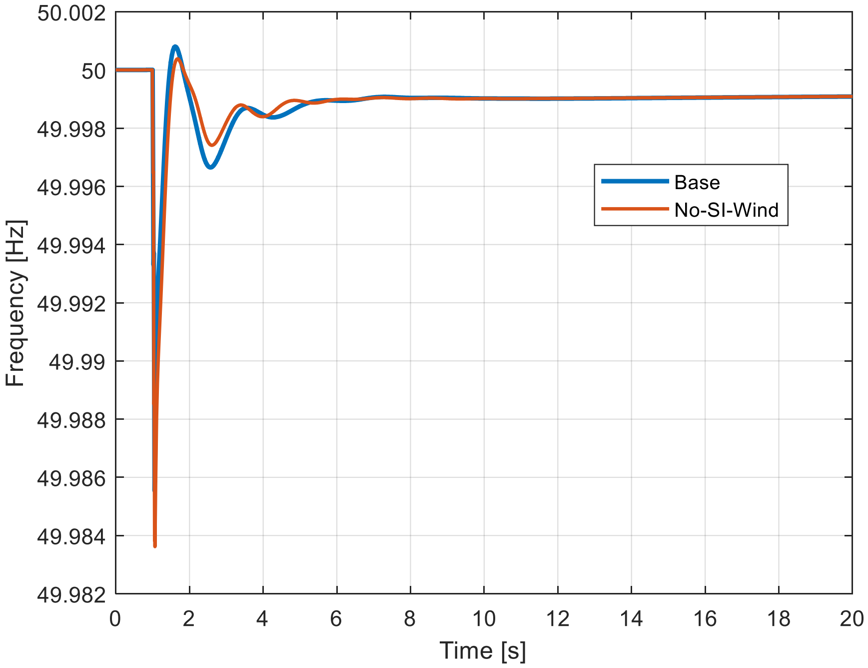

Figure 50. Network: 2030. Dispatching profile: Low Load / Low Gas, Event: outage of two of the three connections with continental Italy. Frequency profiles.

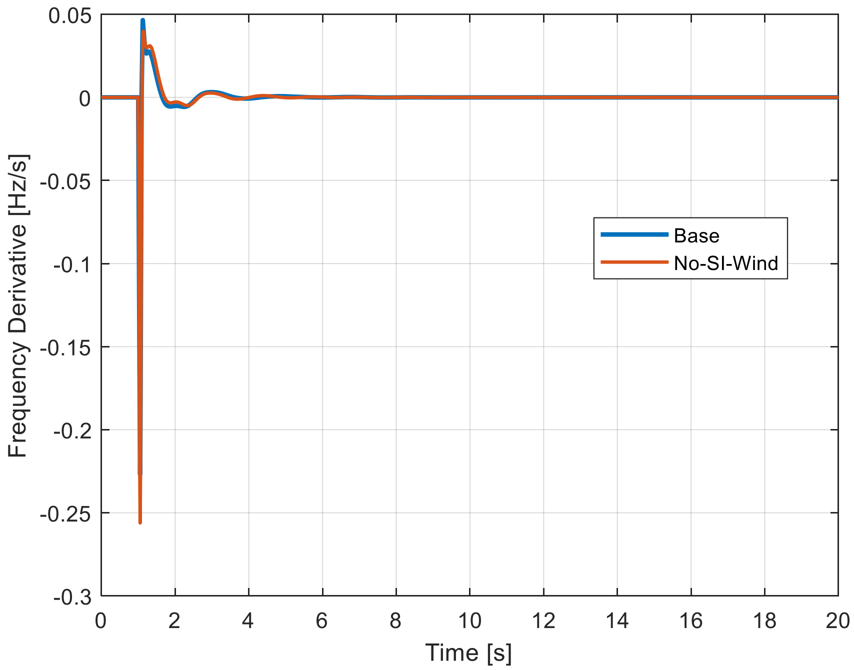

Figure 51. Network: 2030. Dispatching profile: Low Load / Low Gas, Event: outage of two of the three connections with continental Italy. Frequency derivative profiles.

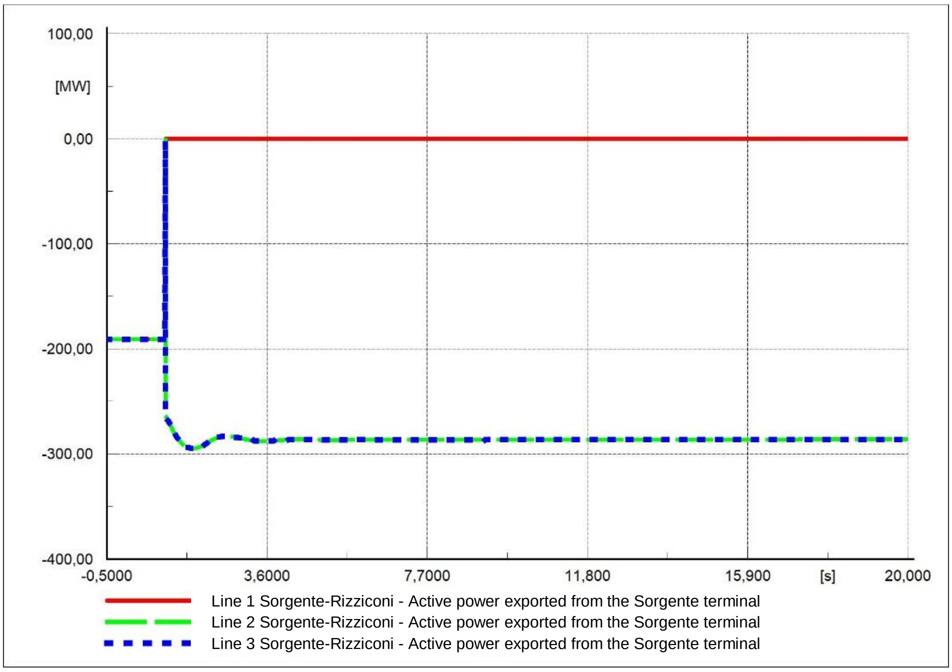

Figure 52. Network: 2030. Dispatching profile: Low Load / Low Gas, Event: outage of two of the three connections with continental Italy, base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

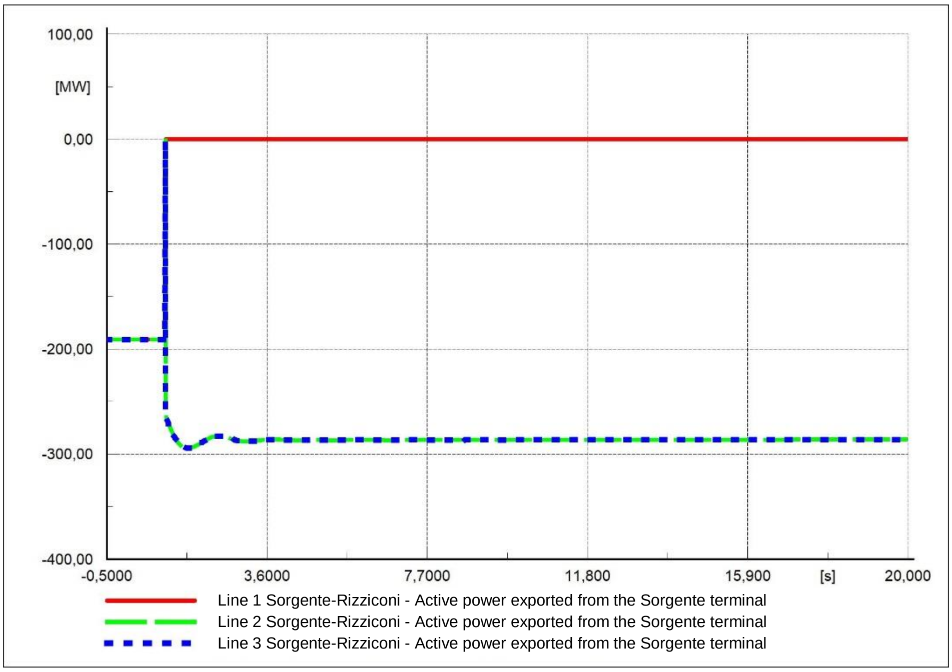

Figure 53. Network: 2030. Dispatching profile: Low Load / Low Gas, Event: outage of two of the three connections with continental Italy, No-SI-Wind configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.5.3 Outage of Termini Imerese Power Plant CC, GT1 and GT2

The following Figure 54 and Figure 55 report the simulation results obtained with the outage of Termini Imerese Power Plant CC, GT1 and GT2. In this case, the generation loss (337 MW) causes a decrease of frequency. The resulting quasi-steady-state frequency value is around 49.945 Hz. Without the SI provided by wind generators, the maximal frequency deviation and the maximal frequency derivative are slightly higher. In any case, frequency stability is guaranteed.

Figure 56 and Figure 57 show the power exchanged through the three connections with continental Italy in the base and No-SI-Wind configurations, respectively. It can be observed that the power import increases (in the figures a negative value indicates power import from continental Italy to Sicily) in response to the large loss of generation caused by the simulated outage.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 0.93 kA.

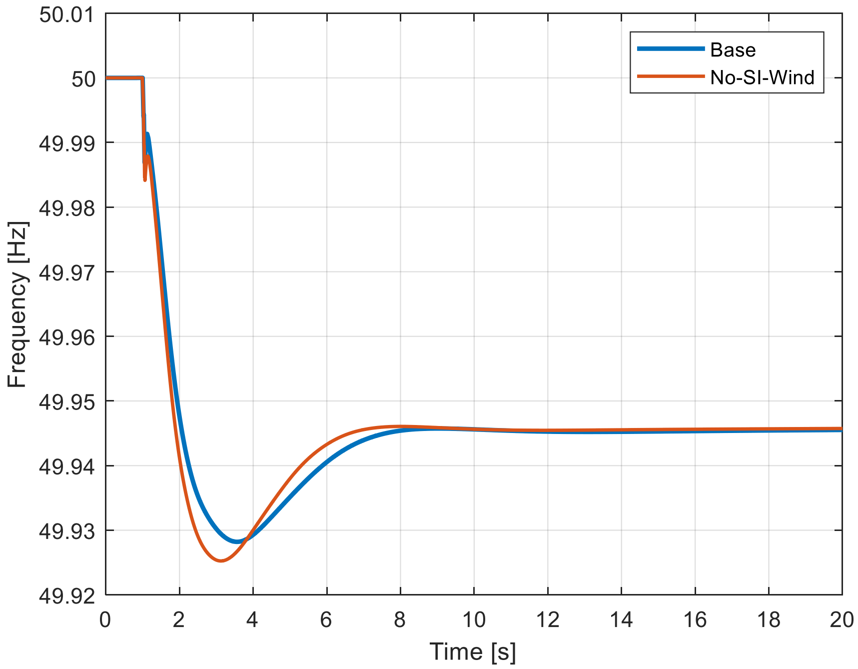

Figure 54. Network: 2030. Dispatching profile: Low Load / Low Gas, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 337 MW of generated power), base configuration. Frequency profiles.

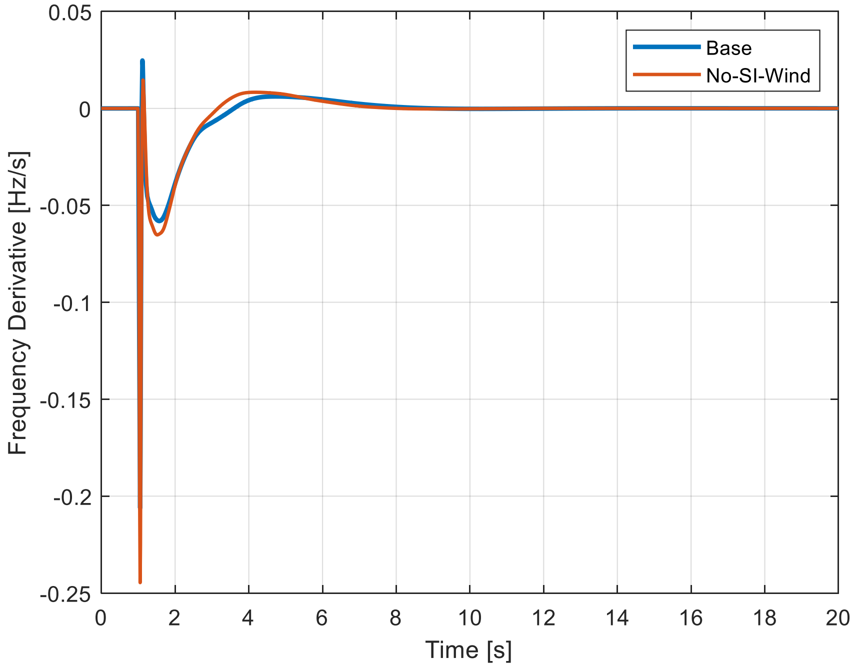

Figure 55. Network: 2030. Dispatching profile: Low Load / Low Gas, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 337 MW of generated power), base configuration. Frequency derivative profiles.

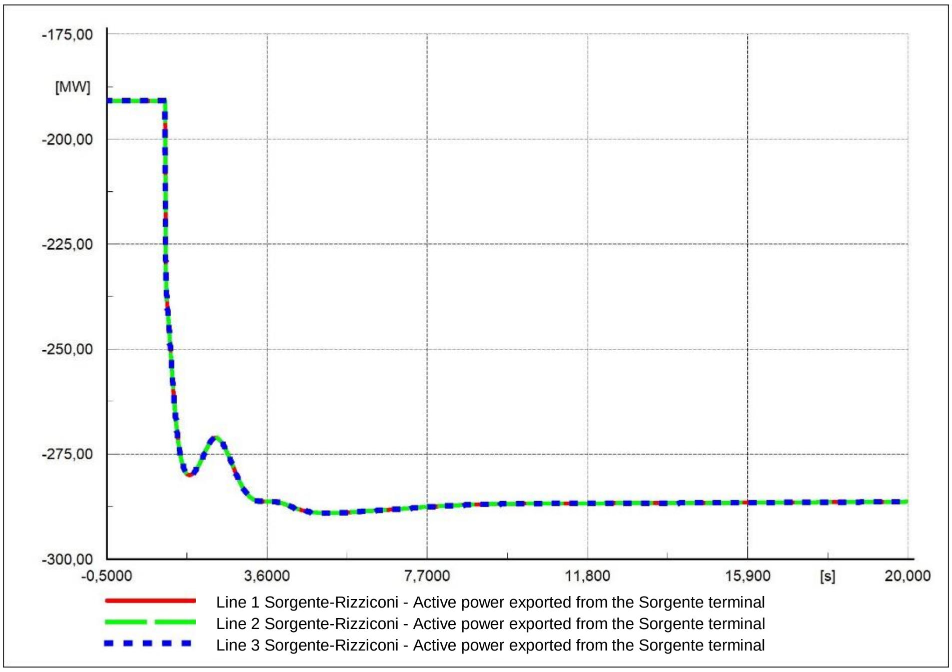

Figure 56. Network: 2030. Dispatching profile: Low Load / Low Gas, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 337 MW of generated power), base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

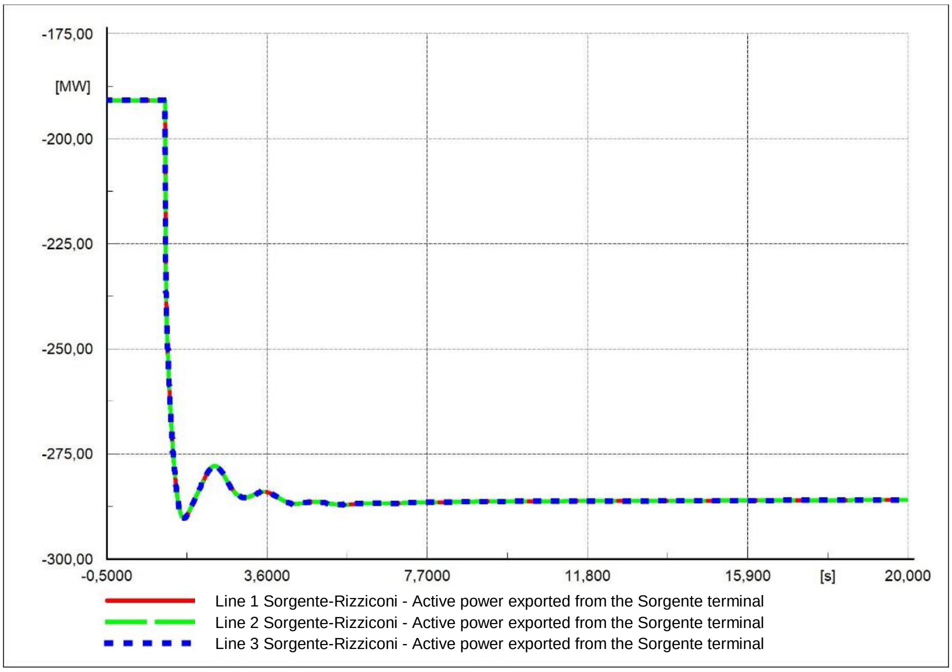

Figure 57. Network: 2030. Dispatching profile: Low Load / Low Gas, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 337 MW of generated power), No-SI-Wind configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.6 Lines out of service dispatching profile

In this dispatching profile, the events reported in the following have been simulated:

- outage of one of the three connections with continental Italy;
- outage of two of the three connections with continental Italy;
- outage of Termini Imerese Power Plant CC, GT1 and GT2 (Snom = 946 MVA): loss of 337 MW of generated power.

4.3.1.6.1 Outage of one of the three connections with continental Italy

The following Figure 58 and Figure 59 report the simulation results obtained with the loss of one of the three connections from continental Italy. It can be observed that frequency stability is always guaranteed, also without the SI operated by wind generators.

Figure 60 and Figure 61 show the power exchanged through the three connections with continental Italy in the base and No-SI-Wind configurations, respectively. It can be observed that the power imported by the lost connection is distributed to the two remaining connections.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 0.93 kA.

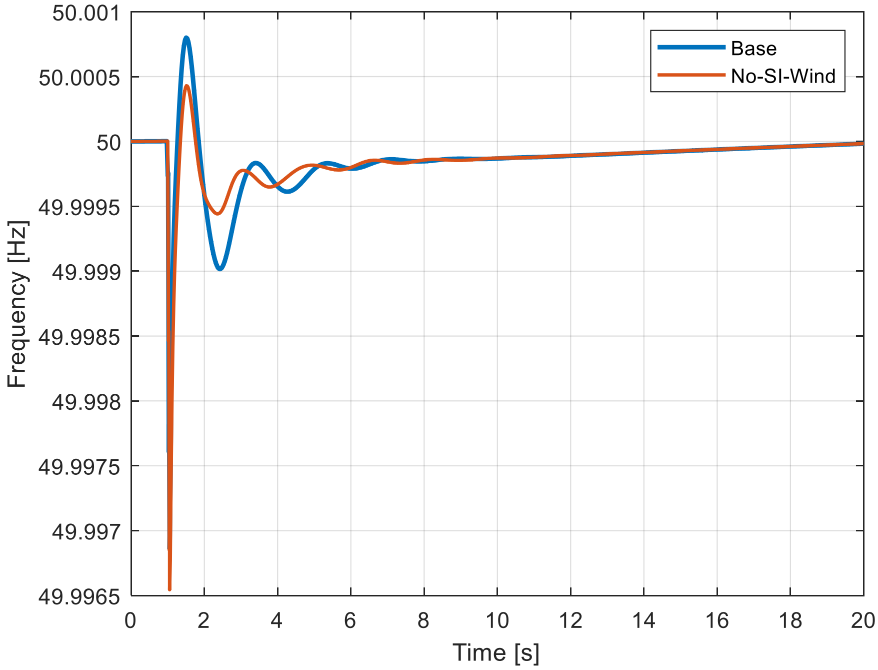

Figure 58. Network: 2030. Dispatching profile: Lines out of service, Event: outage of one of the three connections with continental Italy. Frequency profiles.

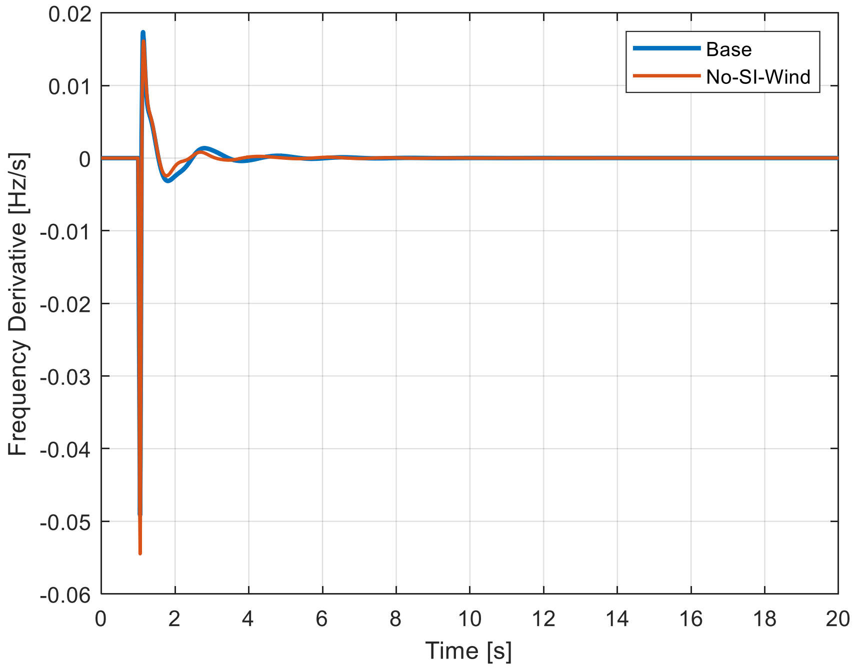

Figure 59. Network: 2030. Dispatching profile: Lines out of service, Event: outage of one of the three connections with continental Italy. Frequency derivative profiles.

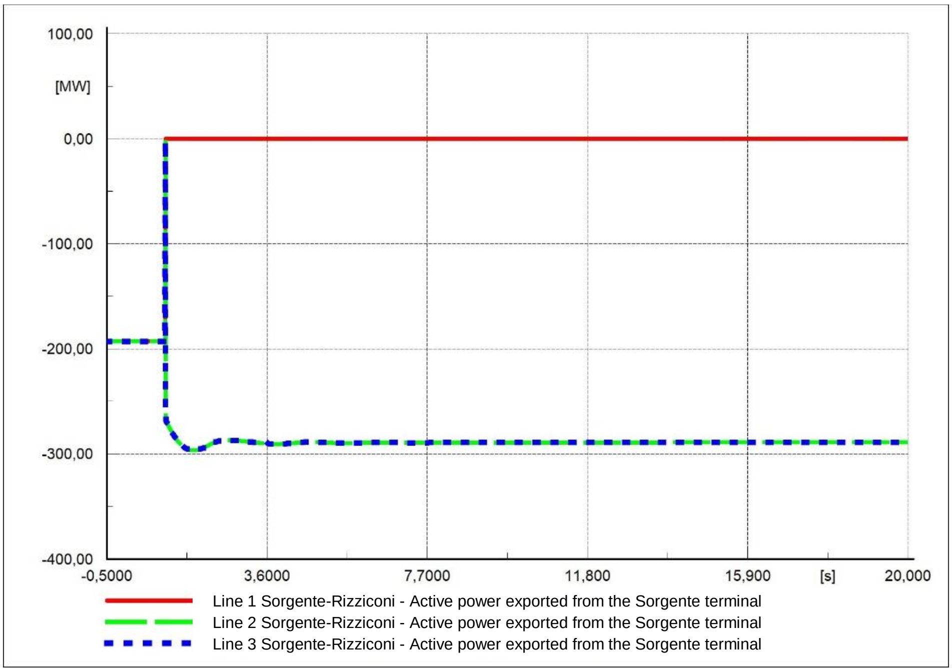

Figure 60. Network: 2030. Dispatching profile: Lines out of service, Event: outage of one of the three connections with continental Italy, base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

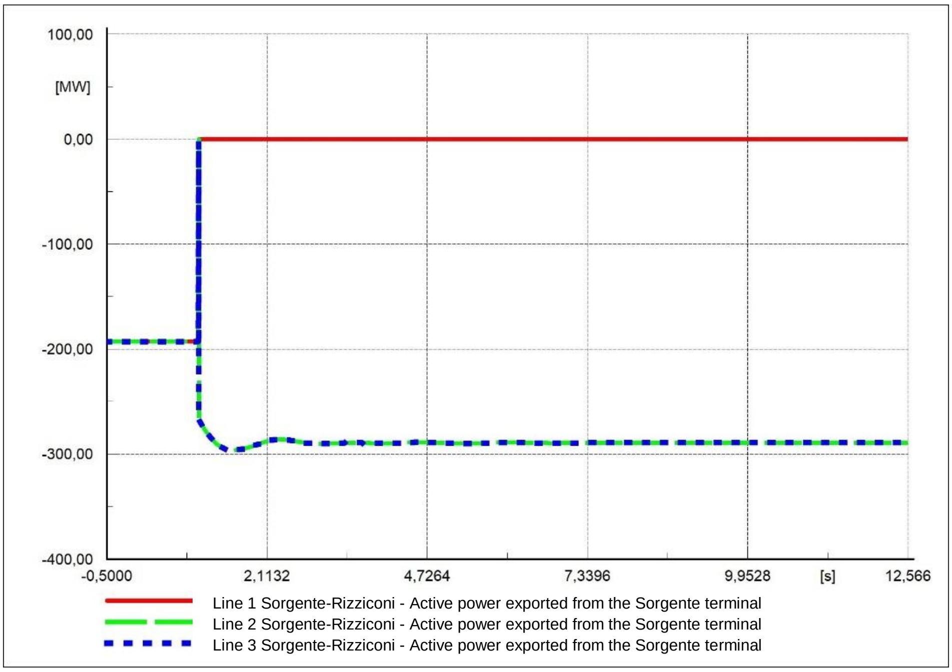

Figure 61. Network: 2030. Dispatching profile: Lines out of service, Event: outage of one of the three connections with continental Italy, No-SI-Wind configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.6.2 Outage of one of the three connections with continental Italy

The following Figure 62 and Figure 63 report the simulation results obtained with loss of two of the connection with continental Italy. In this case, frequency stability is guaranteed both with and without the SI provided by wind generators.

Figure 64 and Figure 65 show the power exchanged through the three connections with continental Italy in the base and No-SI-Wind configurations, respectively. It can be observed that the power imported by the lost connections is entirely imported by third one.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 0.93 kA.

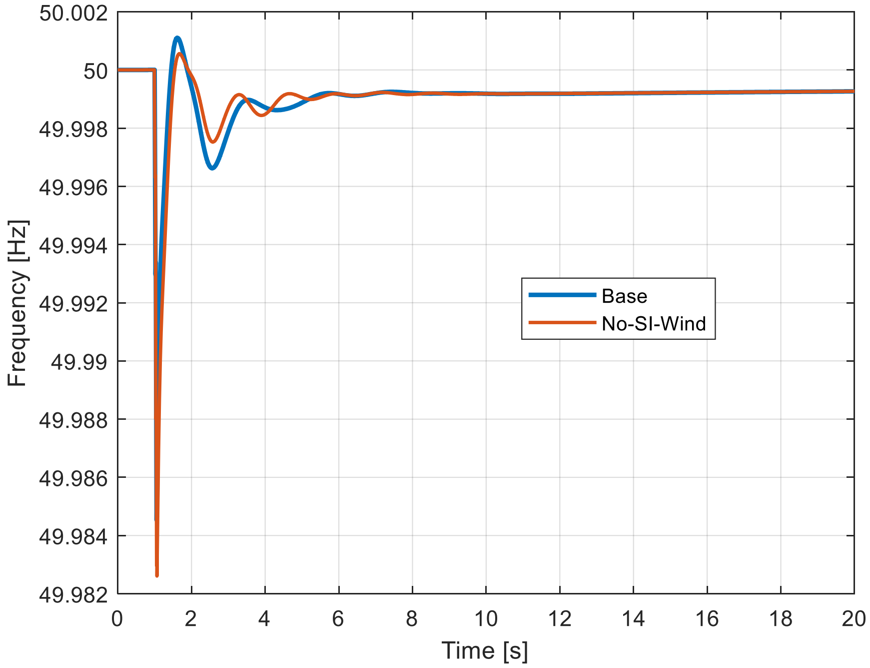

Figure 62. Network: 2030. Dispatching profile: Lines out of service, Event: outage of two of the three connections with continental Italy. Frequency profiles.

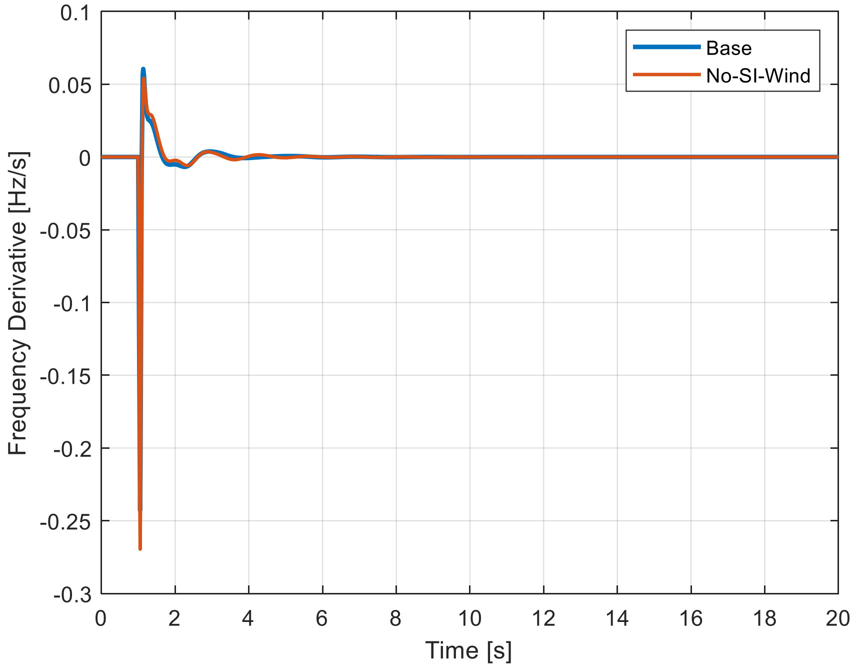

Figure 63. Network: 2030. Dispatching profile: Lines out of service, Event: outage of two of the three connections with continental Italy. Frequency derivative profiles.

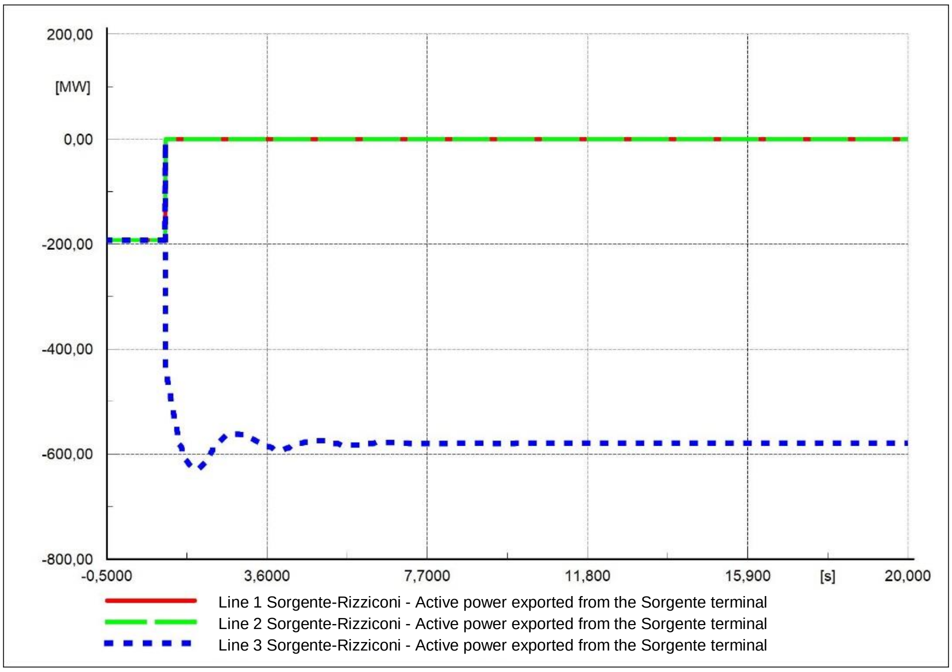

Figure 64. Network: 2030. Dispatching profile: Lines out of service, Event: outage of two of the three connections with continental Italy, base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

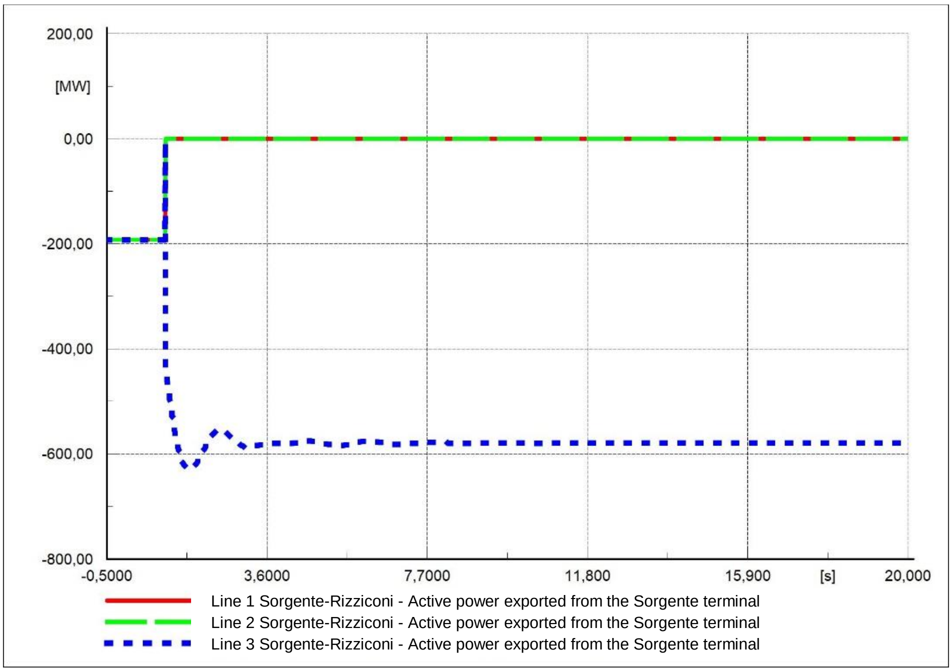

Figure 65. Network: 2030. Dispatching profile: Lines out of service, Event: outage of two of the three connections with continental Italy, No-SI-Wind configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.6.3 Outage of Termini Imerese Power Plant CC, GT1 and GT

The following Figure 66 and Figure 67 report the simulation results obtained with the outage of Termini Imerese Power Plant CC, GT1 and GT2. In this case, the generation loss (337 MW) causes a decrease of frequency. The resulting quasi-steady-state frequency value is around 49.925 Hz. Without the SI provided by wind generators, the maximal frequency deviation and the maximal frequency derivative are slightly higher. In any case, frequency stability is guaranteed.

Figure 68 and Figure 69 show the power exchanged through the three connections with continental Italy in the base and No-SI-Wind configurations, respectively. It can be observed that the power import increases (in the figures, a negative value indicates power import from continental Italy to Sicily) in response to the large loss of generation caused by the simulated outage.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 0.93 kA.

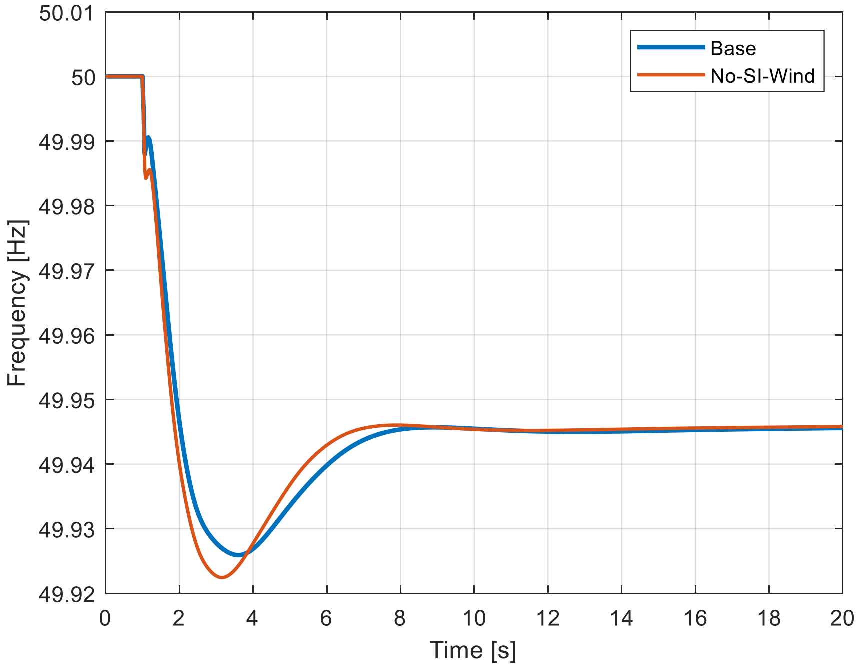

Figure 66. Network: 2030. Dispatching profile: Lines out of service, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 337 MW of generated power), base configuration. Frequency profiles.

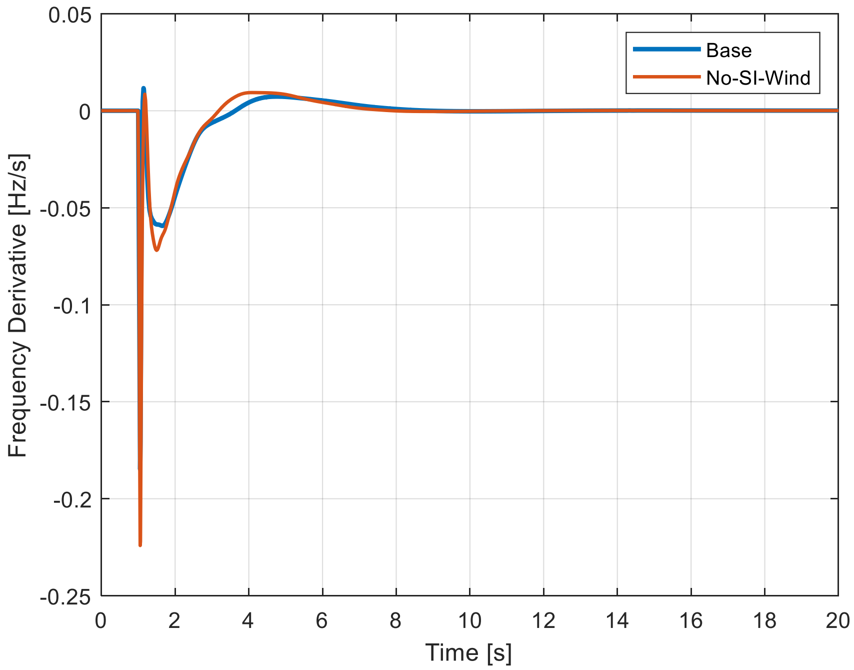

Figure 67. Network: 2030. Dispatching profile: Lines out of service, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 337 MW of generated power), base configuration. Frequency derivative profiles.

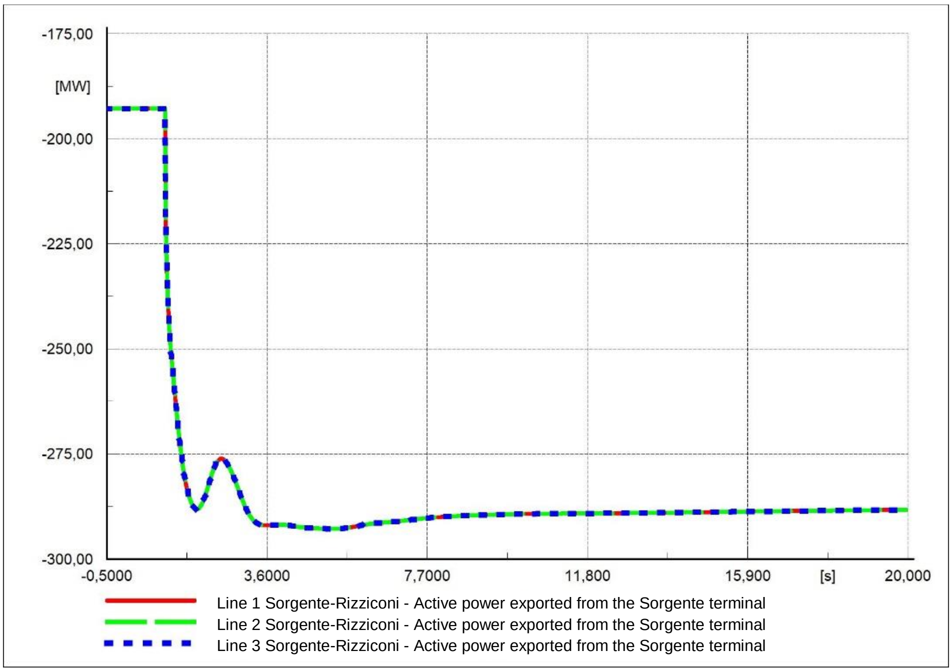

Figure 68. Network: 2030. Dispatching profile: Lines out of service, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 337 MW of generated power), base configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

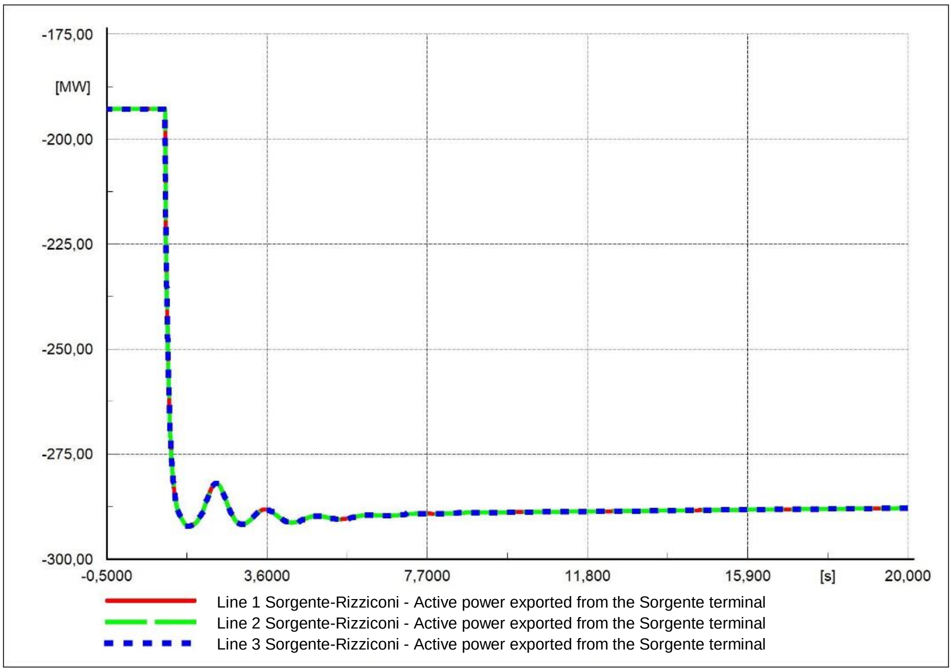

Figure 69. Network: 2030. Dispatching profile: Lines out of service, Event: outage of Termini Imerese Power Plant CC, GT1 and GT2 (loss of 337 MW of generated power), No-SI-Wind configuration. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.1.7 2030 Conclusions

The frequency stability of the power system of Sicily, forecasted for the year 2030, has been analysed. Six different dispatching profiles have been studied:

1. **High Export**, characterized by quite high PV production, and a consequent high-power export from Sicily to continental Italy;
2. **High Import**: characterized by almost zero PV production, high load demand, and a consequent high level of power import from continental Italy to Sicily;
3. **High Load / Low Gas**, characterized by high load, high PV, medium wind and low traditional generation production;
4. **Island**, which is the *High Load / Low Gas* profile when the link with the mainland is out of service;
5. **Low Load / Low Gas**, characterized by low load and low production by thermal plants, and medium wind production;
6. **Lines out of service**, which is the *Low Load / Low Gas* profile with two lines out of service.

In each dispatching profile, a set of events has been simulated to study the frequency dynamical response. Specifically, since Sicily is (and will be at least) connected with continental Italy through three AC lines, the outage of one and two of these connections has been simulated in all the profiles (except for the *Island* one). Moreover, the outage of a group of traditional generating units has been simulated as a severe imbalance event.

According to the forecasts, wind generators are assumed to provide Synthetic Inertia (SI). To analyse the effect of this SI to the power system dynamics, all simulations have been executed both with and without the SI contribution of wind generators.

In all the cases where the connection with continental Italy is kept, even if with one or two of the three cables, frequency does not exit from the normal operating conditions which, according to the current Italian grid code [19], is defined by the range 49.9 Hz – 50.1 Hz.

This occurs both with and without the SI provided by wind generators. However, SI allows the maximal frequency deviation and the maximal frequency derivative to be reduced. Such an effect results to be relatively small since when the connection with continental Italy is in service, the overall system inertia is huge, if compared with the portion provided by the wind generators installed in Sicily.

In the *Island* profile, 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 (which in the islanded case is defined by the range 49.5 Hz – 50.5 Hz) and stability can be only guaranteed by load shedding. In this case, the provision of a power reserve (FCR) from the modulation of flexible loads (DSR) has been considered. In the specific simulated case, a power reserve of 127 MW has resulted to be enough to avoid the shedding of 707 MW, keeping the frequency within the normal operating condition limits. In this case, therefore, this flexibility option is paramount.

A second critical situation has been detected in the *High Import* profile. Here, the outage of two of the three connections with continental Italy, because of the high level of import, 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 (this possibility should be managed in the operational planning stage). 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.

After the islanding, frequency stability is guaranteed by load shedding and the contribution of SI provided by wind generators results to be more evident. Indeed, without SI, frequency derivative is significantly high all the levels of load shedding are activated (953 MW). Differently, with the provision SI, load shedding is reduced to 738 MW. As for the *Island*, the provision of a power reserve (FCR) from the modulation of flexible loads (DSR) has been tested in this case. DSR has resulted to be useful to reduce the frequency derivative and the maximal frequency deviation; load shedding is not avoided but reduced to 523 MW.

The general conclusions of this study are that, based on the forecast for 2030:

- when Sicily is connected with continental Italy, frequency stability is guaranteed with no difficulties;
- SI allows the maximal frequency deviation and the maximal frequency derivative to be reduced;
- when Sicily is islanded, frequency stability can be guaranteed using load shedding or, if present, introducing DSR;
- no voltage problems or congestion issues have appeared during simulations.

4.3.2 2050 Network

In the forecasted scenario for Sicily in 2050, according to results provided in WP1, there are battery energy storage systems (BESSs) that can provide FFR. Moreover, DSR provided by loads can be considered to be available. Therefore, in each dispatching profile and for each event, the **base configuration** without BESS FFR and DSR FFR is firstly tested. Then, if frequency stability cannot be guaranteed, further network configurations with BESS FFR and\or DSR FFR will be simulated to assess their effectiveness in solving technical issues. On the contrary, SI is always assumed to be in operation at wind power plants.

The configuration of the DSR FFR is indicated with DSR-p, as done in the case of the Network 2030 (see Section 4.3.1 for details), with the same common parameters provided in Table 8. Table 11 reports the list of the loads associated to the DSR models and their operating points for each profile.

	Active Power [MW]					
Name	**High Export**	**High Import**	**High Load**	**Island**	**Low Load**	**Lines out of service**
Load 1	42.8	42.8	59.92	59.92	21.4	21.4
Load 2	13.8	27.6	38.64	38.64	13.8	13.8
Load 3	14.5	29	40.6	40.6	14.5	14.5
Load 4	13.9	27.8	38.92	38.92	13.9	13.9
Load 5	13.3	26.6	37.24	37.24	13.3	13.3
Load 6	15	30	42	42	15	15
Load 7	126.6	189.9	177.24	177.24	0	0
Load 8	13.5	27	37.8	37.8	13.5	13.5
Load 9	16.9	33.8	47.32	47.32	16.9	16.9
Load 10	15	30	42	42	15	15
Load 11	13.4	26.8	37.52	37.52	13.4	13.4
Load 12	52.4	52.4	73.36	73.36	26.2	26.2
Load 13	13.8	27.6	38.64	38.64	13.8	13.8
Load 14	13.6	27.2	38.08	38.08	13.6	13.6
Load 15	14.8	29.6	41.44	41.44	14.8	14.8
Load 16	13.3	26.6	37.24	37.24	13.3	13.3
TOTALS	**406.6**	**654.7**	**827.96**	**827.96**	**232.4**	**232.4**

Table 11. Loads associated with the DSR models in Network 2050.

As described in [16], BESS FFR is implemented as primary droop controller essentially defined by two parameters: the dead-band, which is set to 10 mHz, and the droop coefficient b [%] which states the amount of FCR provided by the BESS. Specifically, given the i-th BESS with nominal power $P_{BESS,i}^{nom}$ [MW], the BESS will provide, at steady-state, a power variation:

$$\Delta P_{BESS,i} = \frac{100}{b} \frac{\Delta f}{f^{nom}} P_{BESS,i}^{nom} \tag{2}$$

In this study, the same droop coefficient is assumed for all BESSs in service with values within the interval 1 ÷ 5 %, and the relevant network configuration is indicated with BESS-b. It is worth noticing that 4 - 5 % are typical droop coefficient values adopted for traditional (hydro or thermal) generators. In this study, lower values are considered since BESSs could potentially be installed to exclusively provide FFR and therefore droop can be lowered more than in the case of generators. In particular, since the simulated BESSs are associated to wind and traditional generators, and their nominal power are assumed equal to the 20 % of the relevant generators, a droop coefficient equal to 1 % means that the BESS is emulating the 5 % droop frequency response of the associated generator. Obviously, a general hypothesis is that BESSs are provided with the required energy reserve, *i.e.,* their State of Charge (SoC) is such that the required power variation can be kept up to a prescribed maximal time interval (a typical value is 15 minutes).

By adopting Δf_{max} = 0.2 Hz as the frequency deviation at which the full FCR should be released (according to [20]), the FCR provided by the i^{th} BESS is

$$K_{BESS,i} = \min\left(\frac{100}{b} * \frac{0.2}{f^{nom}} * P^{nom}_{BESS,i}, P^{nom}_{BESS,i} - \left|P^0_{BESS,i}\right|\right) \quad (3)$$

where $P^0_{BESS,i}$ is the i-th BESS working point. In the following, K_{BESS} will indicate the total FCR provided by all BESSs providing FFR, $i.e.$

$$K^{tot}_{BESS} = \sum_i K_{BESS,i} \quad (4)$$

Moreover, K^{tot} will indicate the total FCR provided by BESSs and DSR, *i.e.*,

$$K^{tot} = K^{tot}_{BESS} + K^{tot}_{DSR} \quad (5)$$

In the following subsections, results obtained for each simulation are reported.

4.3.2.1 High Export dispatching profile

In this dispatching profile, the events reported in the following have been simulated:

- **load-step occurring in continental Italy:** emulation of the loss of 500 MW of generated power;
- **outage of one of the three connections with continental Italy;**
- **outage of two of the three connections with continental Italy;**
- **outage of Priolo Gargallo Nuce Nord units G1, G2, GC, CG (Snom = 390 MVA) and the corresponding BESSs (Snom = 78 MVA):** total loss of 220 MW of injected power.

The DSR and BESS FCR network configurations listed in 12 have been considered when necessary.

Network Configuration	K^{tot}_{BESS} [MW]	K^{tot}_{DSR} [MW]	K^{tot} [MW]	% DSR	% Loads Operating 5 % DSR	% Loads Operating 10 % DSR
BESS-4	138	0	138	0 %	0 %	0 %
BESS-2	277	0	277	0 %	0 %	0 %
BESS-2 DSR-25	277	101	378	5 %	110 %	55 %
BESS-2 DSR-35	277	142	419	8 %	155 %	77 %
BESS-1 DSR-25	554	101	655	5 %	110 %	55 %

*Total Load = 1837 MW

Table 12. Network 2050. Dispatching profile: "High-Export". DSR/BESS FCR network configuration parameters.

4.3.2.1.1 Load-step in continental Italy

The following Figure 70 and Figure 71 report the simulation results obtained with the 500 MW load-step in continental Italy. We can observe that without the contribution of DSR and BESSs, the limit of 49.9 Hz for normal operating conditions is violated. A total additive reserve of 655 MW, realized with the configuration BESS-1 DSR-25 (see 12), is required to keep frequency higher than 49.9 Hz. In any case, stability is guaranteed also without the support DSR and/or BESSs.

Figure 72 shows the power exchanged through the three connections with continental Italy. We can observe as the contribution to regulation provided from Sicily increases, as expected, as the BESSs droop coefficient decreases and as the percentage of loads operating DSR increases.

Figure 73 shows the active power exchanged by the BESSs associated to in-service traditional generators, Full Converter Wind Turbines (FCWT) and Double Fed Induction Generator (DFIG) wind turbines. Here, BESSs are exporting power when simulation starts. Then, when the perturbation occurs, they increase their power export to support the frequency regulation. As expected, the provided power variation is higher as lower is the droop coefficient.

Figure 74 reports the variation of the active power absorbed by loads operating DSR. We can observe that, as frequency decreases, the power demand is reduced to support frequency regulation. Clearly, the contribution of loads is higher as higher is the percentage of participating loads.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

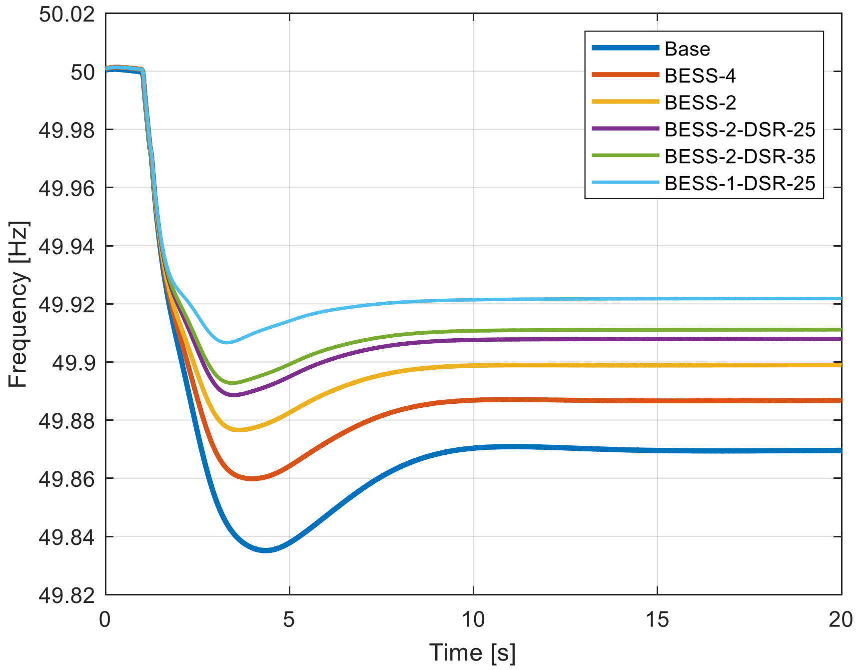

Figure 70. Network: 2050. Dispatching profile: High Export, Event: load-step in continental Italy. Frequency profiles.

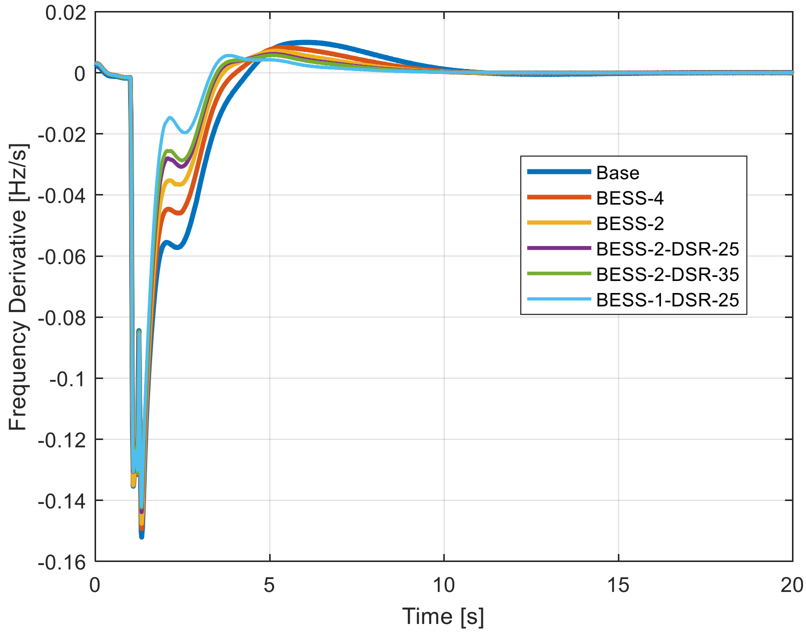

Figure 71. Network: 2050. Dispatching profile: High Export, Event: load-step in continental Italy. Frequency derivative profiles.

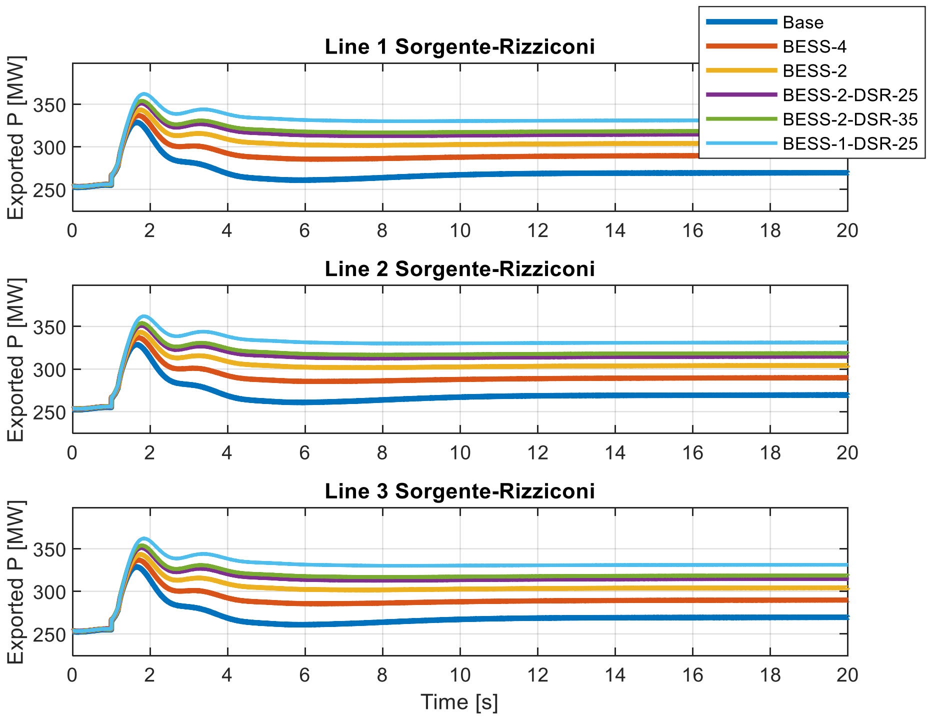

Figure 72. Network: 2050. Dispatching profile: High Export, Event: load-step in continental Italy. Power exported from the Sorgente terminal through the three connections with continental Italy.

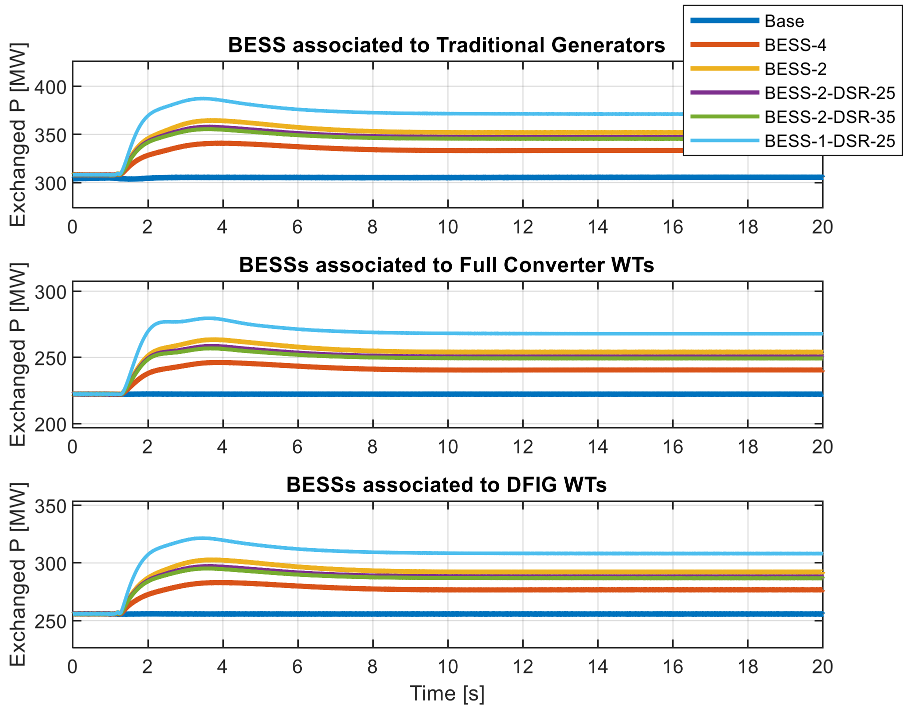

Figure 73. Network: 2050. Dispatching profile: High Export, Event: load-step in continental Italy. Power exchanged by BESSs (positive means export, negative means import).

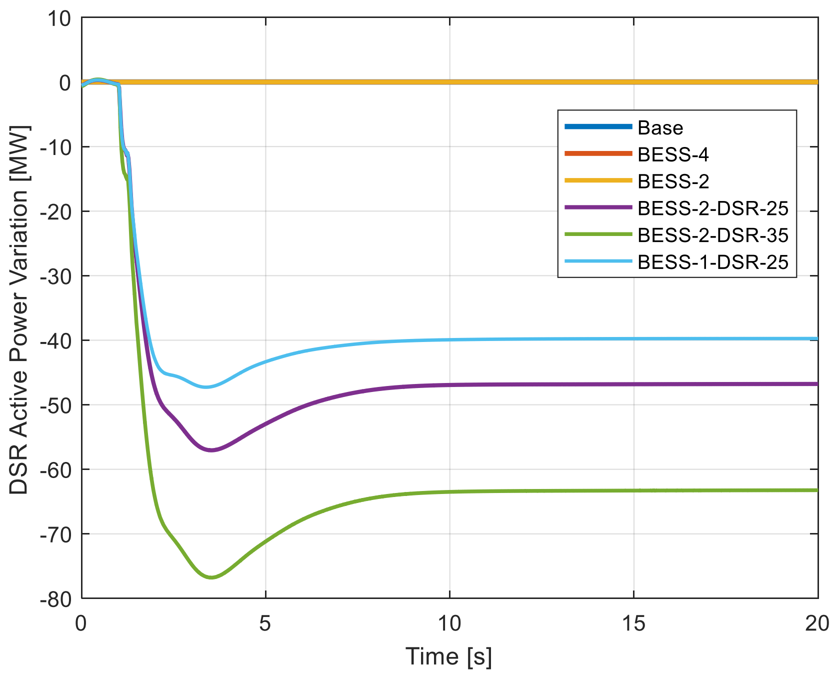

Figure 74. Network: 2050. Dispatching profile: High Export, Event: load-step in continental Italy. Total power consumption variation provided by DSR.

4.3.2.1.2 Outage of one of the three connections with continental Italy

The following Figure 75 and Figure 76 report the simulation results obtained with the loss of one of the three connections with continental Italy. It can be observed that frequency stability is guaranteed without using BESSs and DSR.

Figure 134 shows the power exchanged through the three connections with continental Italy. We can observe that the power exported by the lost connection is distributed to the two remaining connections.

We verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

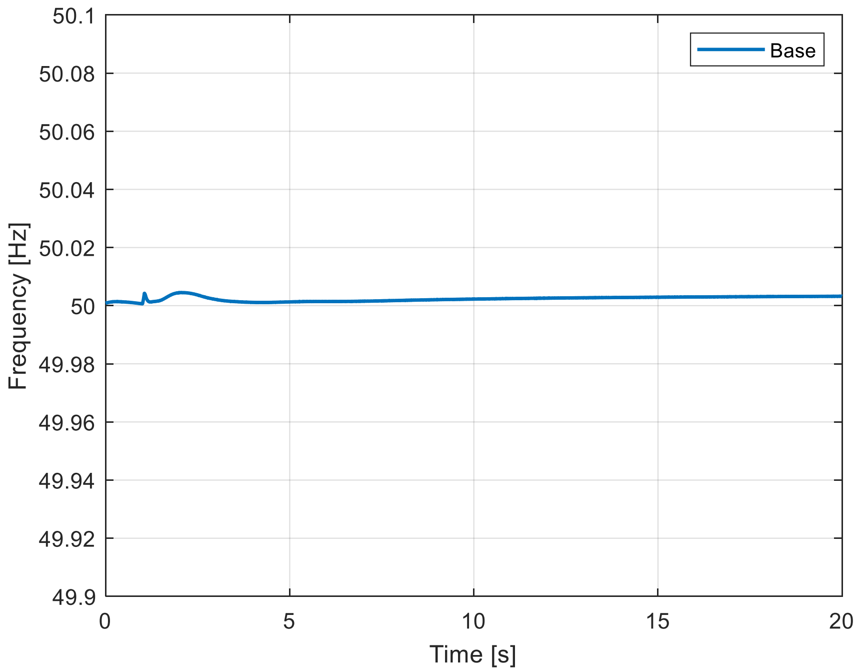

Figure 75. Network: 2050. Dispatching profile: High Export, Event: outage of one of the three connections with continental Italy. Frequency profiles.

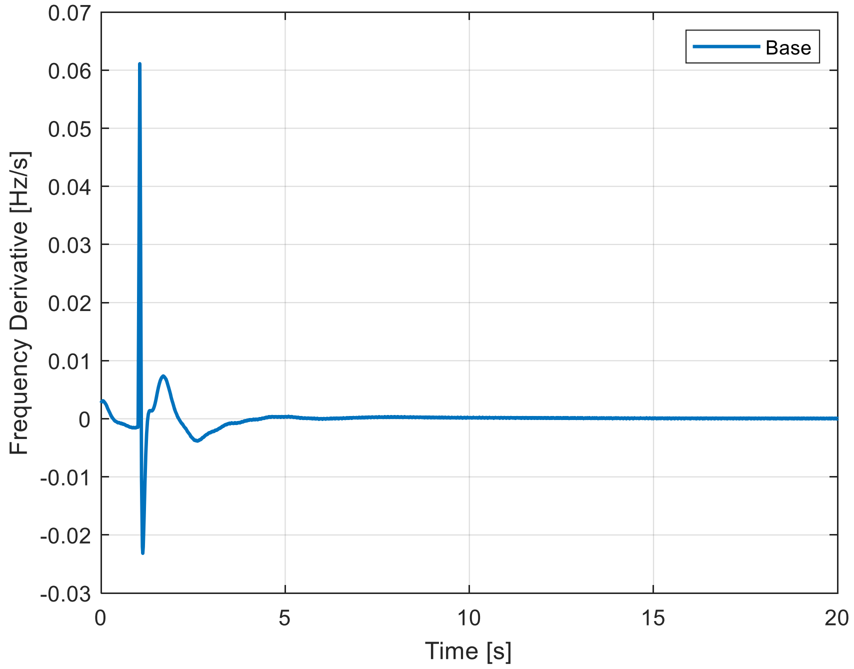

Figure 76. Network: 2050. Dispatching profile: High Export, Event: outage of one of the three connections with continental Italy. Frequency derivative profiles.

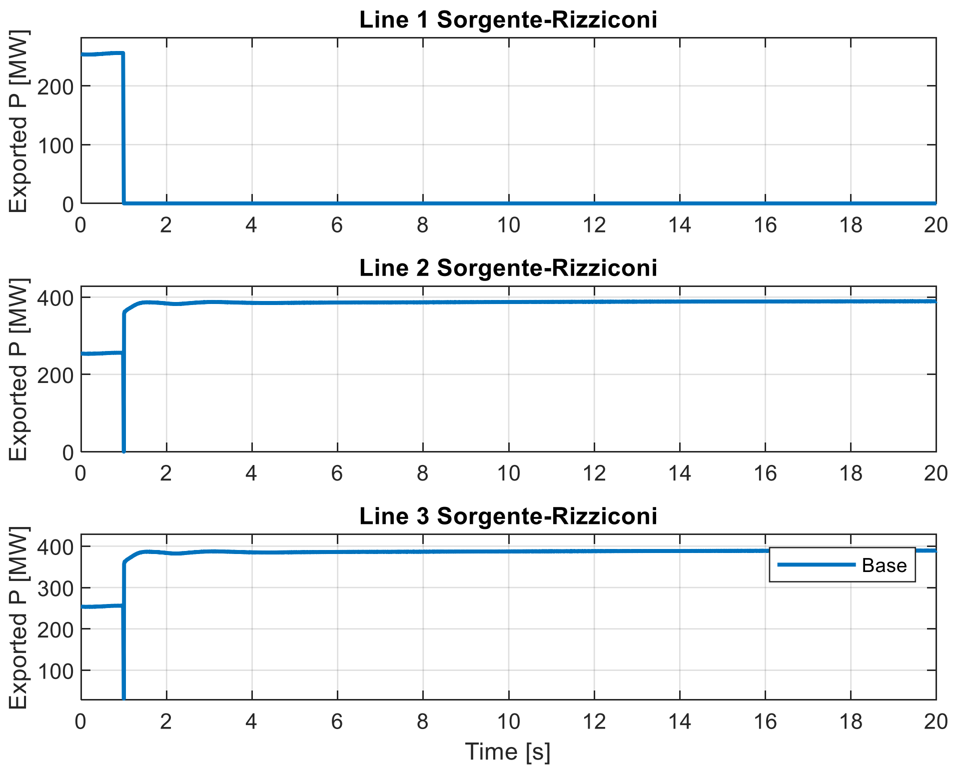

Figure 77. Network: 2050. Dispatching profile: High Export, Event: outage of one of the three connections with continental Italy. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.2.1.3 Outage of two of the three connections with continental Italy

The following Figure 78 and Figure 79 report the simulation results obtained with the loss of two of the three connections with continental Italy. It can be observed that frequency stability is guaranteed without using BESSs and DSR.

Figure 80 shows the power exchanged through the three connections with continental Italy. We can observe that the power exported by the two lost connections is covered by the third connection.

We verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

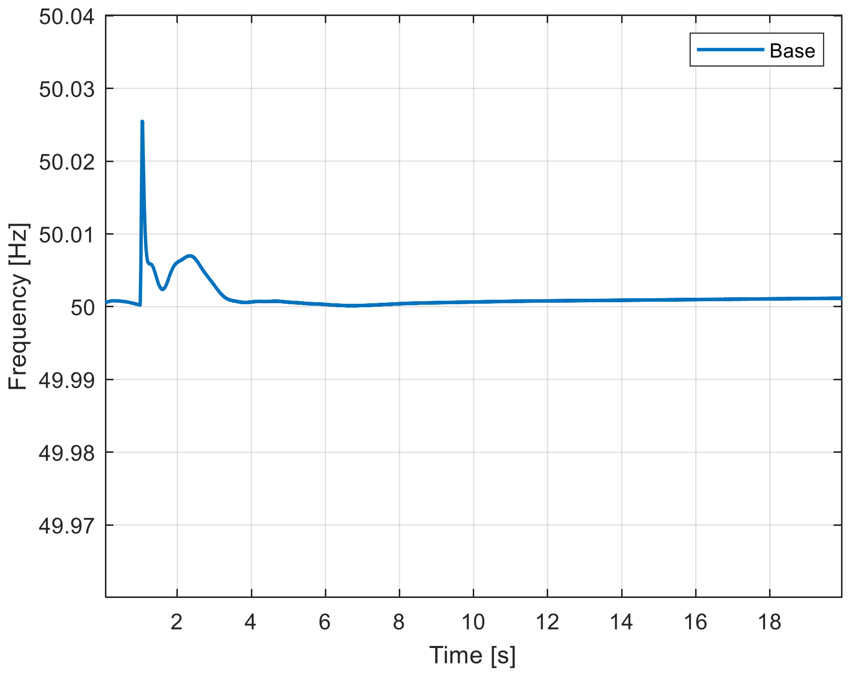

Figure 78. Network: 2050. Dispatching profile: High Export, Event: outage of two of the three connections with continental Italy. Frequency profiles.

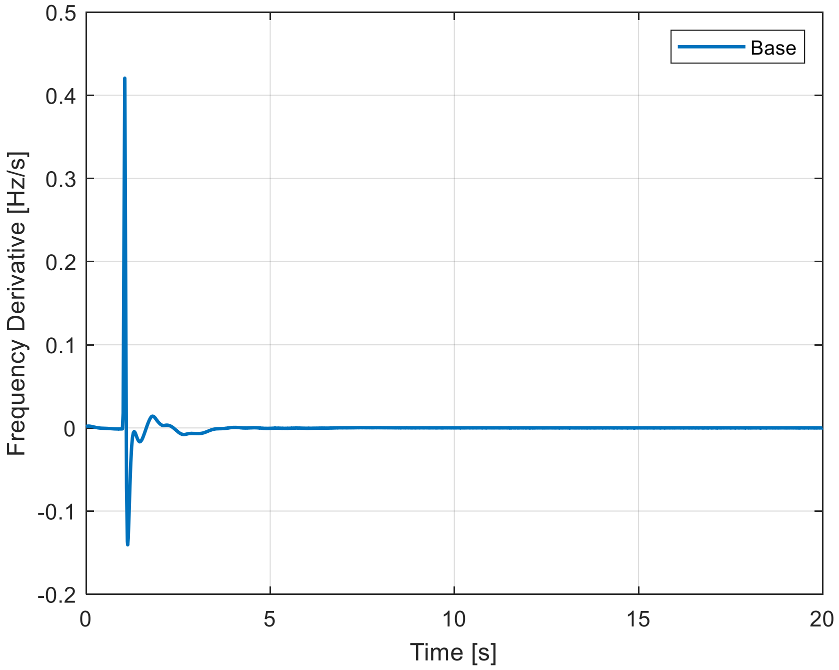

Figure 79. Network: 2050. Dispatching profile: High Export, Event: outage of two of the three connections with continental Italy. Frequency derivative profiles.

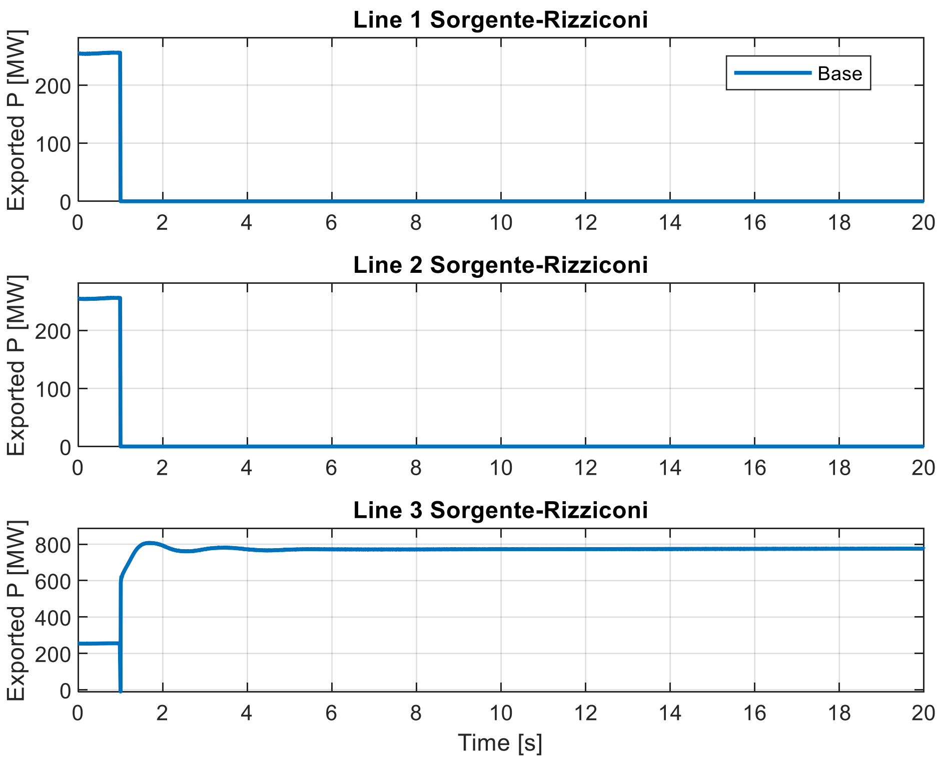

Figure 80. Network: 2050. Dispatching profile: High Export, Event: outage of two of the three connections with continental Italy. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.2.1.4 Outage of Priolo Gargallo Nuce Nord units and the corresponding BESSs

The following Figure 81 and Figure 82 report the simulation results obtained with the outage of Priolo Gargallo Nuce Nord units and the corresponding BESSs (total loss of 220 MW of generated power and BESSs output). Frequency stability is guaranteed without using BESSs and DSR since frequency is always higher than the normal operating conditions limit of 49.9 Hz.

Figure 82 shows the power exchanged through the three connections with continental Italy. We can observe that export is reduced because of the loss of generation occurring in Sicily.

Figure 84 shows the active power exchanged by all BESSs associated to in-service traditional generators, FCWT and DFIG plants. Here, BESSs are exporting power when simulation starts. At 1 second, the power exported by BESSs associated by traditional generators is reduced because the ones related to the Priolo Gargallo Nuce Nord units are disconnected. Moreover, we can observe that no variation is provided to support frequency regulation since FCR has been not activated in this case, because unnecessary.

We verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

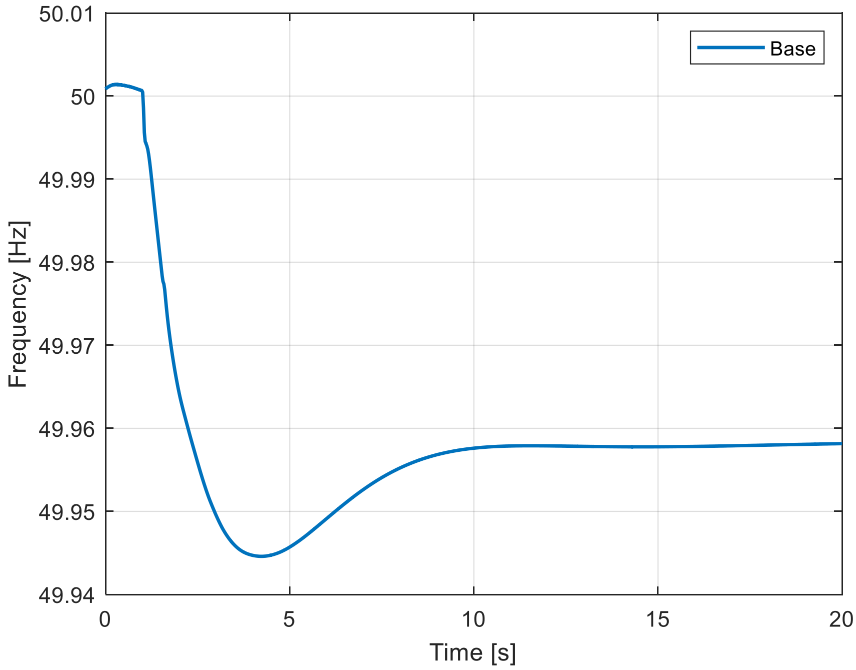

Figure 81. Network: 2050. Dispatching profile: High Export, Event: outage of Priolo Gargallo Nuce Nord units and the corresponding BESSs. Frequency profiles.

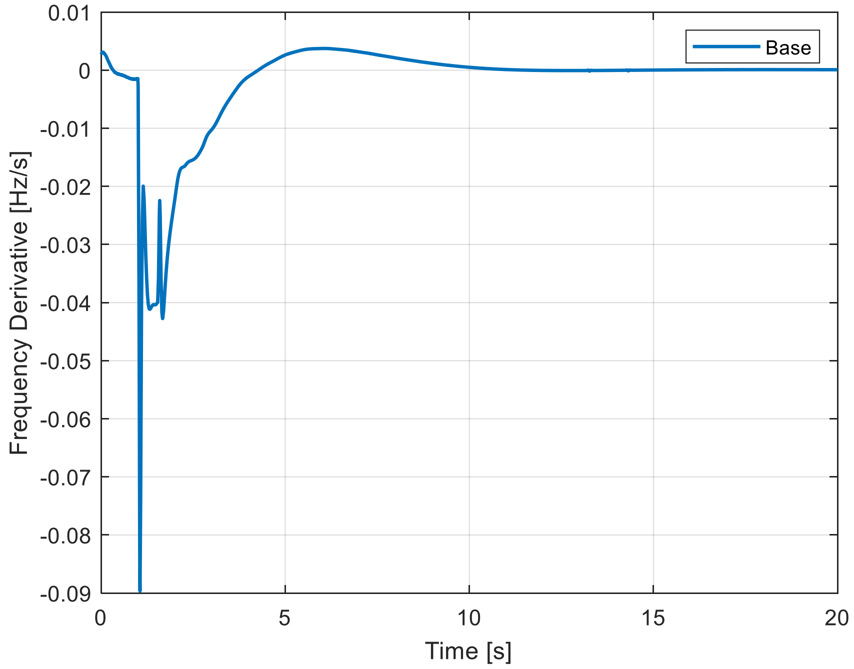

Figure 82. Network: 2050. Dispatching profile: High Export, Event outage of Priolo Gargallo Nuce Nord units and the corresponding BESSs. Frequency derivative profiles.

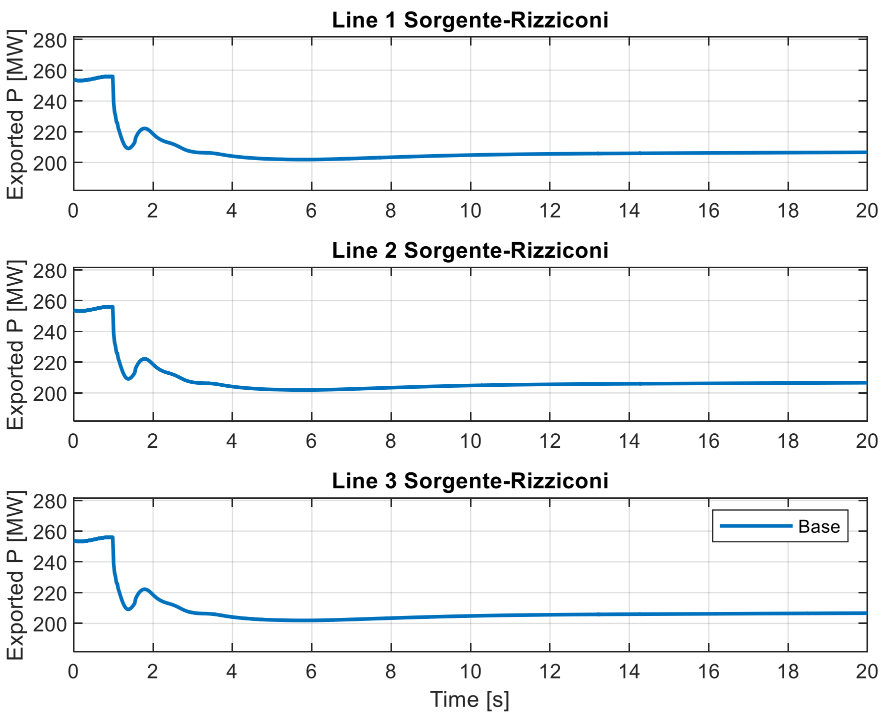

Figure 83. Network: 2050. Dispatching profile: High Export, Event: outage of Priolo Gargallo Nuce Nord units and the corresponding BESSs. Power exported from the Sorgente terminal through the three connections with continental Italy.

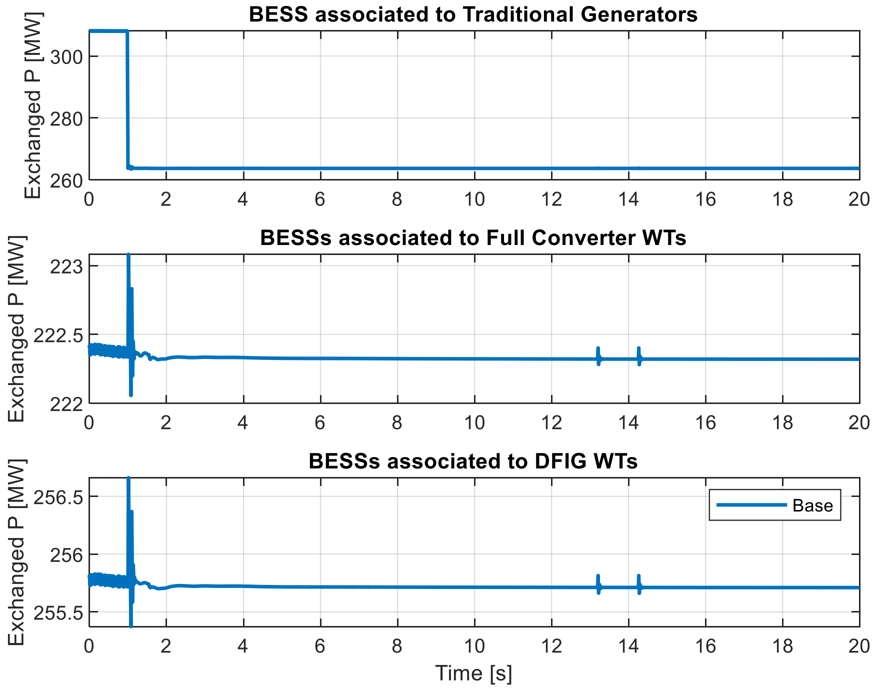

Figure 84. Network: 2050. Dispatching profile: High Export, Event: outage of Priolo Gargallo Nuce Nord units and the corresponding BESSs. Power exchanged by BESSs (positive means export, negative means import).

4.3.2.2 High Import dispatching profile

In this dispatching profile, the events reported in the following have been simulated:

- **load-step occurring in continental Italy:** emulation of the loss of 500 MW of generated power;
- **outage of one of the three connections with continental Italy**;
- **outage of two of the three connections with continental Italy**;
- **outage of Termini Imerese unit G1 (Snom = 370 MVA) and the corresponding BESS (Snom = 74 MVA):** total loss of 321 MW of injected power;
- **outage of Termini Imerese units G1 and G2 (Snom = 658 MVA) and the corresponding BESSs (Snom = 132 MVA):** total loss of 569 MW of injected power;
- **outage of All Termini Imerese units (Snom = 946 MVA) and the corresponding BESSs (Snom = 189 MVA):** total loss of 817 MW of injected power.

The DSR and BESS FCR network configurations listed in Table 13 have been considered.

Network Configuration	K_{BESS}^{tot} [MW]	K_{DSR}^{tot} [MW]	K^{tot} [MW]	% DSR	% Loads Operating 5 % DSR	% Loads Operating 10 % DSR
BESS-5	105	0	105	0 %	0 %	0 %
BESS-4	131	0	131	0 %	0 %	0 %
BESS-3	174	0	174	0 %	0 %	0 %
BESS-1	522	0	522	0 %	0 %	0 %
BESS-5 DSR-15	105	98	203	3 %	61 %	30 %
BESS-4 DSR-15	131	98	229	3 %	61 %	30 %
BESS-4 DSR-25	131	164	295	5 %	102 %	51 %
BESS-3 DSR-25	174	164	338	5 %	102 %	51 %
BESS-2 DSR-25	261	164	425	5 %	102 %	51 %
BESS-1 DSR-25	520	164	684	5 %	102 %	51 %
BESS-1 DSR-35	522	229	751	7 %	142 %	71 %

*Total Load = 3218 MW

Table 13. Network 2050. Dispatching profile: "High-Import". DSR/BESS FCR network configuration parameters.

4.3.2.2.1 Load-step in continental Italy

The following Figure 85 and Figure 86 report the simulation results obtained with a 500 MW load-step increase in continental Italy. We can observe that, without the contribution of DSR and BESSs, the limit of 49.9 Hz for normal operating conditions would be violated. A total additive reserve of 203 MW, realized with the configuration BESS-5 DSR-15 (see Table 13), is required to keep frequency higher than 49.9 Hz. In any case, frequency stability is guaranteed also without the support of BESSs and/or DSR.

Figure 87 shows the power exchanged through the three connections with continental Italy. We can observe that the contribution to regulation provided from Sicily increases as the BESSs droop coefficient decreases and the percentage of loads operating DSR increases.

Figure 88 shows the active power exchanged by the BESSs associated to in-service traditional generators, FCWT and DFIG plants. Here, BESSs are not exchanging power when simulation starts. Then, when the perturbation occurs, they increase their power export to support the frequency regulation.

Figure 89 reports the variation of the active power absorbed by loads operating DSR. We can observe that, as frequency decreases, the power demand is reduced to support frequency regulation.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

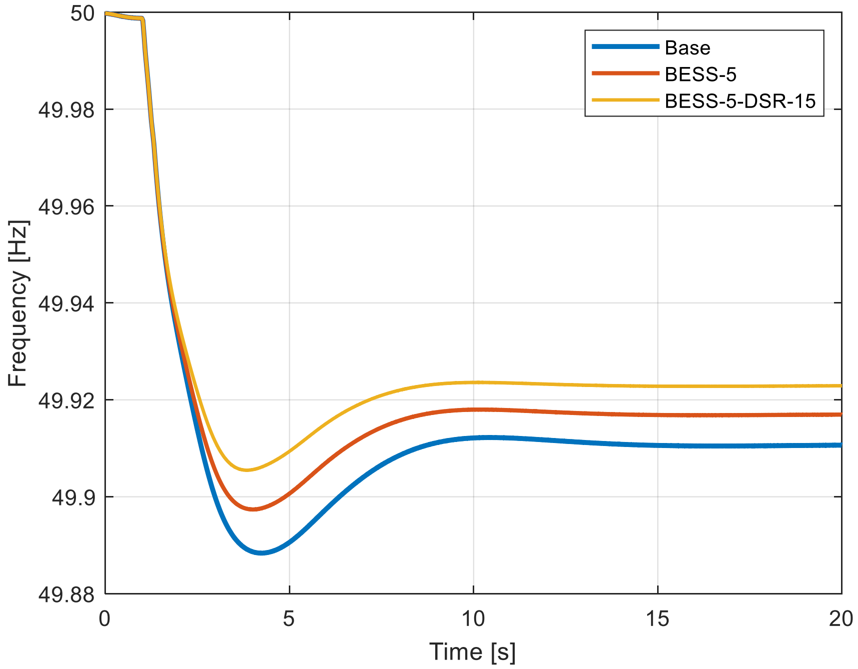

Figure 85. Network: 2050. Dispatching profile: High Import, Event: load-step in continental Italy. Frequency profiles.

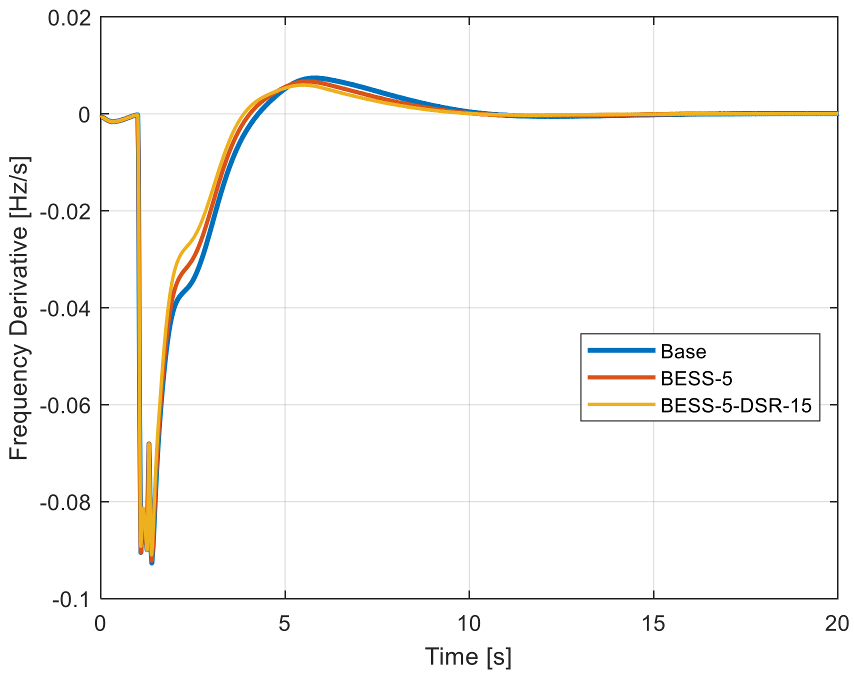

Figure 86. Network: 2050. Dispatching profile: High Import, Event: load-step in continental Italy. Frequency derivative profiles.

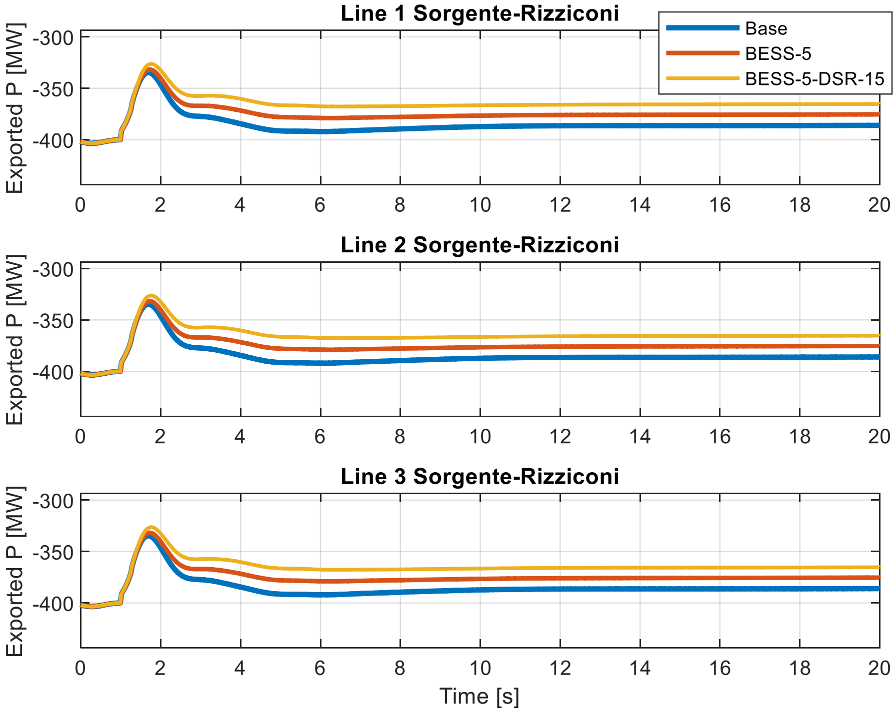

Figure 87. Network: 2050. Dispatching profile: High Import, Event: load-step in continental Italy. Power exported from the Sorgente terminal through the three connections with continental Italy.

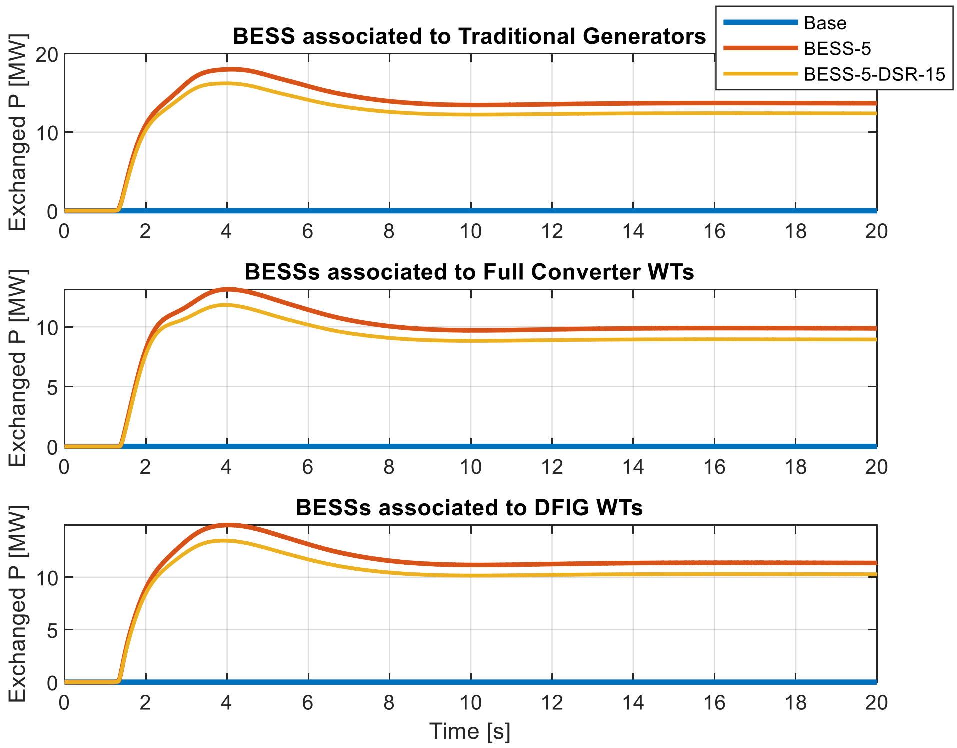

Figure 88. Network: 2050. Dispatching profile: High Import, Event: load-step in continental Italy. Power exchanged by BESSs (positive means export, negative means import).

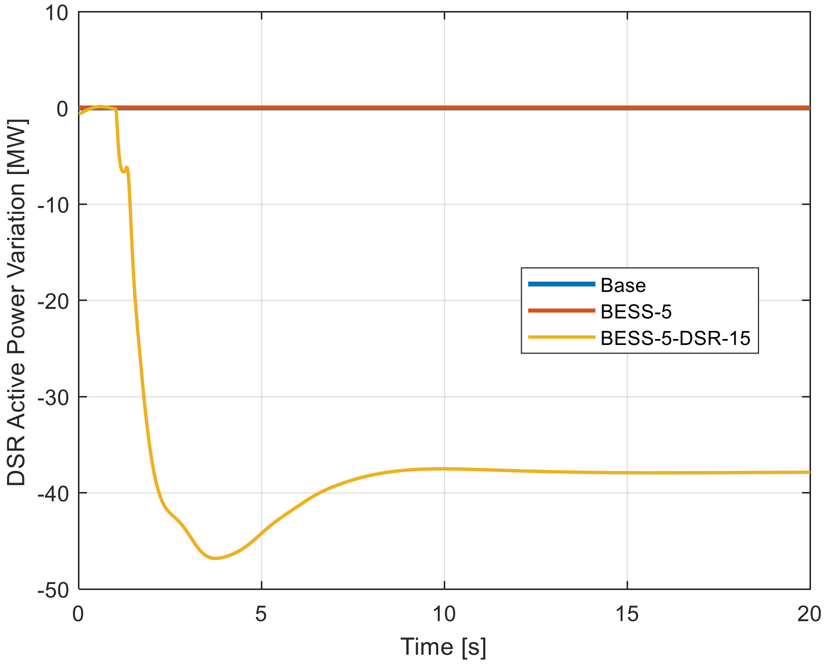

Figure 89. Network: 2050. Dispatching profile: High Import, Event: load-step in continental Italy. Total power consumption variation provided by DSR.

4.3.2.2.2 Outage of one of the three connections with continental Italy

The following Figure 90 and Figure 91 report the simulation results obtained in case of loss of one of the three connections with continental Italy. It can be observed that frequency stability is guaranteed even without using BESSs and DSR.

Figure 92 shows the power exchanged through the three connections with continental Italy. We can observe that the power exported by the lost connection is distributed to the two remaining connections.

We verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

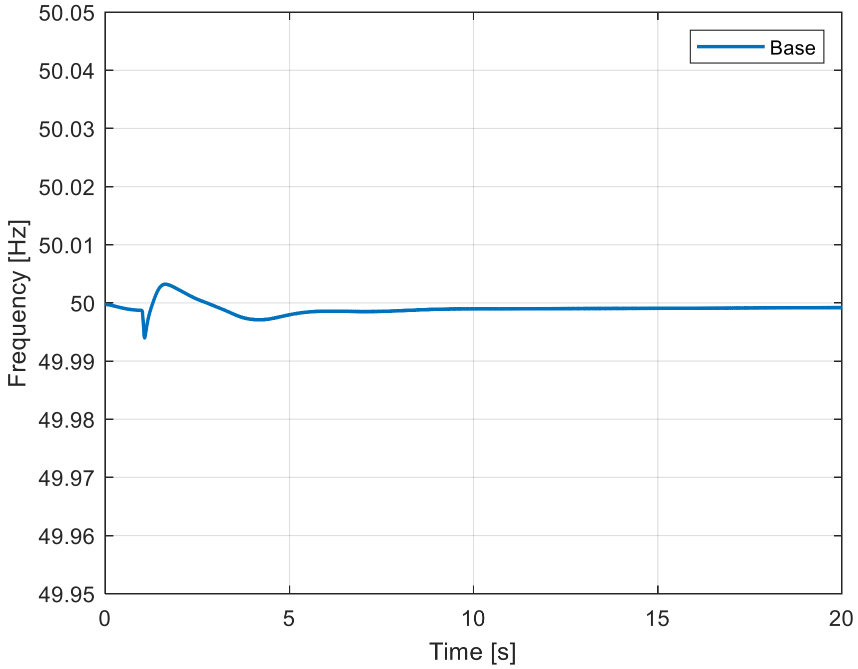

Figure 90. Network: 2050. Dispatching profile: High Import, Event: outage of one of the three connections with continental Italy. Frequency profiles.

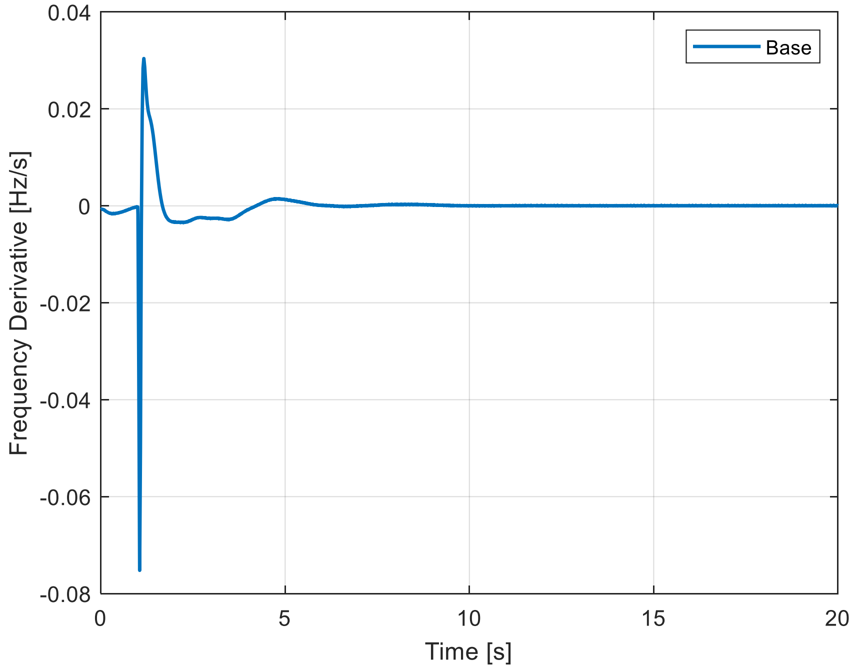

Figure 91. Network: 2050. Dispatching profile: High Import, Event: outage of one of the three connections with continental Italy. Frequency derivative profiles.

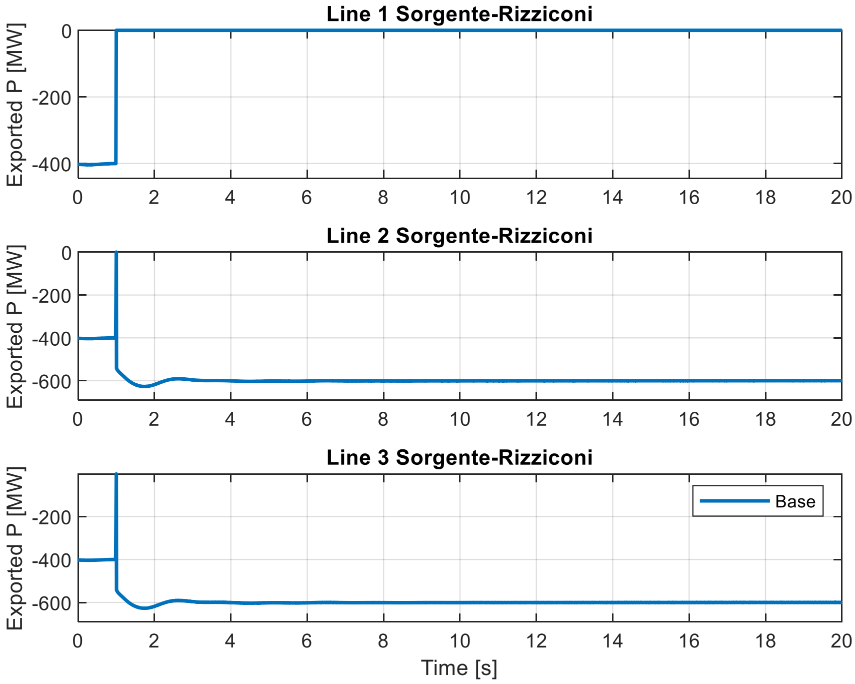

Figure 92. Network: 2050. Dispatching profile: High Import, Event: outage of one of the three connections with continental Italy. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.2.2.3 Outage of two of the three connections with continental Italy

As done for Network 2030, in this subsection, we present the results of a stress test we carried out to check when flexibility resources can become necessary for the stability of the Sicily network. The situation studied is again just proposed here to assess if in this very extreme case flexibility resources can manage the consequent operating conditions. The following Figure 93 and Figure 94 show the results obtained with the outage of two out of the three connections with continental Italy. 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 in facts is not actually present in the real Italian network) leading to its trip and causes the islanding of Sicily. This implies a significant frequency decrease, since 1188 MW of power are lost.

The results of the simulation with the base network configuration are not reported since they are unstable. A first conclusion is therefore that in this dispatching profile, **without the support of BESSs and/or DSR stability cannot be guaranteed**.

In Figure 93, we observe that in configuration BESS-5, with a total additive reserve of 105 MW (see Table 13), frequency reaches a minimum of 48.9 Hz before starting to increase toward a steady-state value of about 49.1 Hz. This is obtained thanks to the **activation of two load shedding steps**. Indeed, at about 2.8 seconds frequency overtakes the threshold of 49.3 Hz and, as shown in the zoom in Figure 94, frequency derivative is lower than -0.3 Hz/s. According to Table 1, this causes the shedding of the 9 % of loads (equal to 290 MW). Then, always according to Table 1, when frequency reaches the threshold of 48.9 Hz a further shedding of the 8 % of loads (equal to 257 MW) is triggered.

Increasing the BESS contribution, in the configuration BESS-3, with a total additive reserve of 174 MW (see Table 13) the shedding at 49.3 Hz is avoided since the overtake of this threshold is delayed at about 3.2 seconds (as we can observe in the zoom in Figure 93) when frequency derivative is higher than the threshold of -0.3 Hz (seconds (as we can observe in the zoom in Figure 94). However, frequency reaches the threshold of 49 Hz, causing the shedding of the 9 % of loads (equal to 290 MW), according to Table 1. Finally, frequency reaches a steady-state value close to 49.3 Hz.

Therefore, with the support of BESSs, in the two configurations BESS-5 and BESS-3, frequency stability is guaranteed, however:

i. load shedding is activated and
ii. normal operating conditions threshold of 49.5 Hz is violated.

Augmenting again the BESS contribution, with a lower droop coefficient, in the configuration BESS-1, with a total additive reserve of 522 MW (see Table 13), **load shedding is avoided, and frequency is kept higher than the 49.5 Hz threshold. A similar result, with a lower frequency deviation is obtained with the BESS-1 DSR-25 configuration, where BESSs and DSR provide a total additive power reserve of 684 MW** (see Table 13).

Figure 95 shows the power exchanged through the three connections with continental Italy. We can observe that the power imported by the third connection fails in covering the power import loss by the first two connections.

Figure 96 shows the active power exchanged by the BESSs associated to in-service traditional generators, FCWT and DFIG plants. Here, BESSs are not exchanging power when simulation starts. Then, when frequency decreases, they increase generating power to support the regulation. We can observe as the BESSs contribution is higher as lower is the droop coefficient.

Figure 97 reports the variation of the active power absorbed by loads operating DSR, which is activated only in the BESS-1 DSR-25 network configuration.

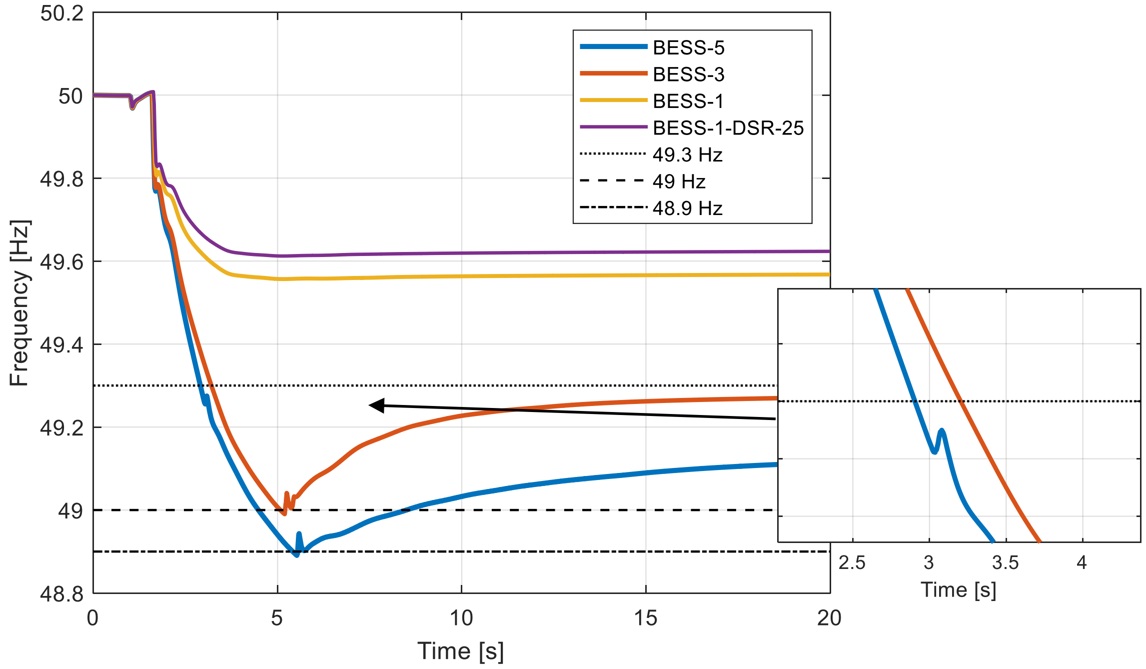

Figure 93. Network: 2050. Dispatching profile: High Import, Event: outage of two of the three connections with continental Italy. Frequency profiles.

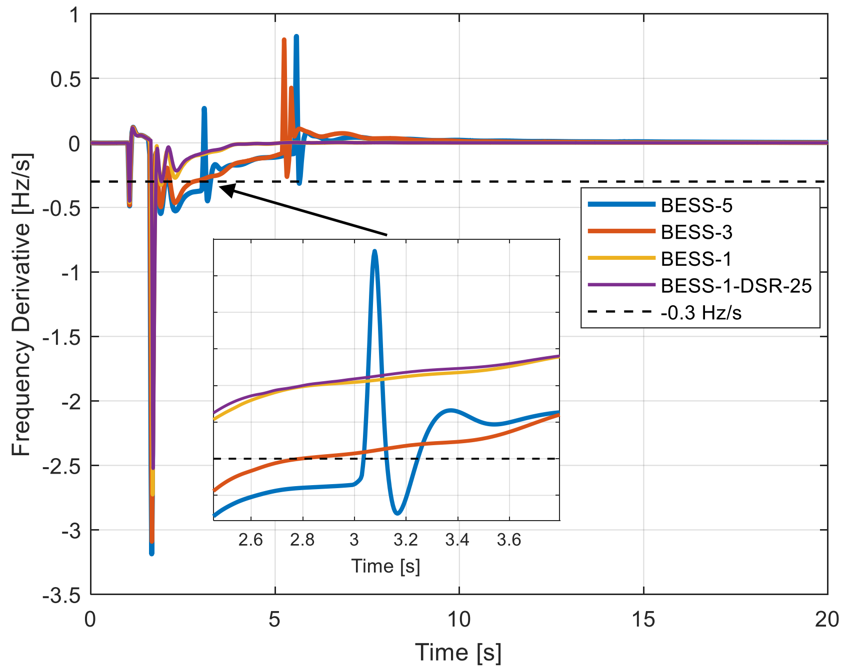

Figure 94. Network: 2050. Dispatching profile: High Import, Event: outage of two of the three connections with continental Italy. Frequency derivative profiles.

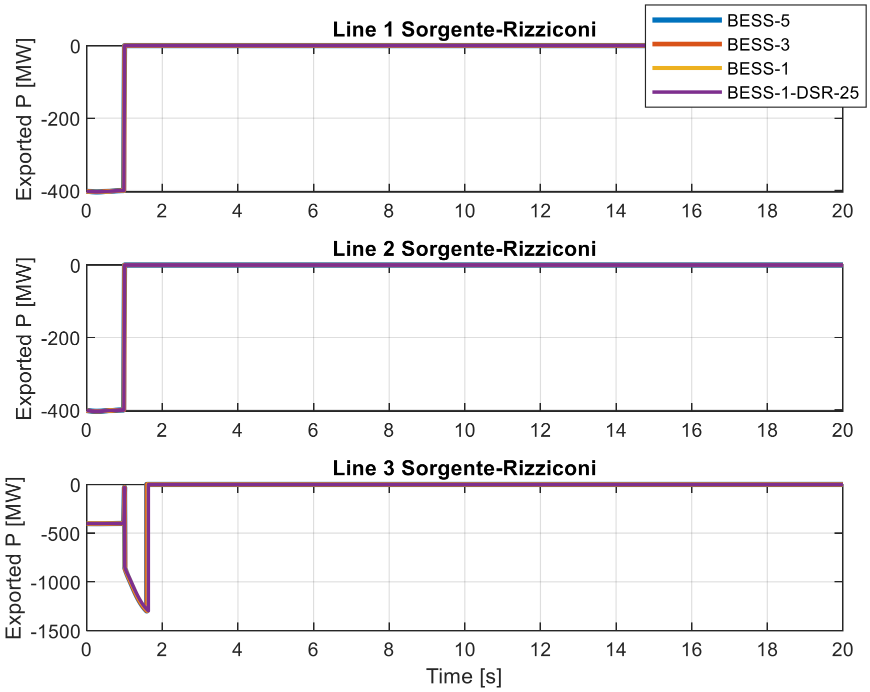

Figure 95. Network: 2050. Dispatching profile: High Import, Event: outage of two of the three connections with continental Italy. Power exported from the Sorgente terminal through the three connections with continental Italy.

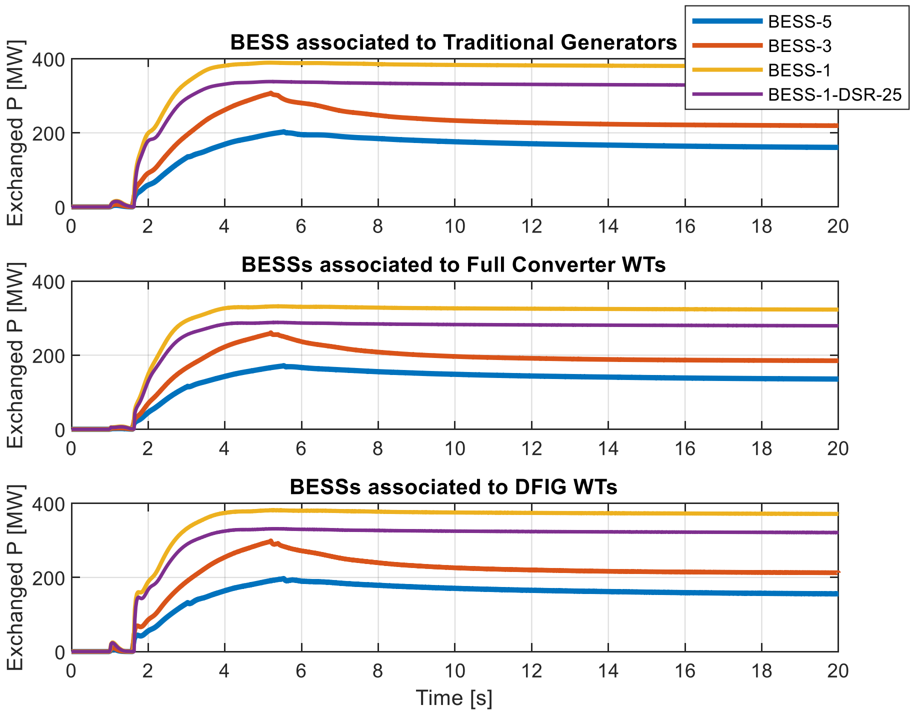

Figure 96. Network: 2050. Dispatching profile: High Import, Event: outage of two of the three connections with continental Italy. Power exchanged by BESSs (positive means export, negative means import).

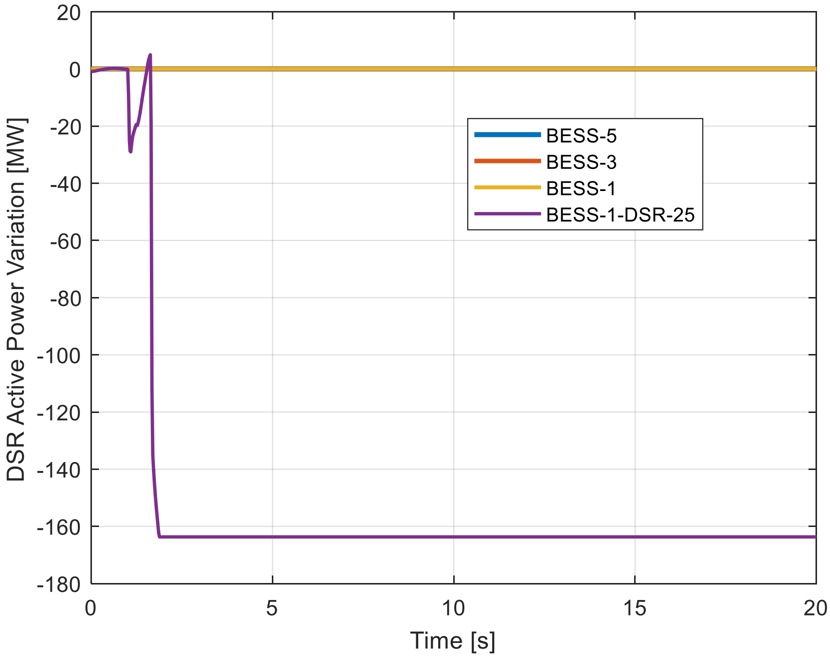

Figure 97. Network: 2050. Dispatching profile: High Import, Event: outage of two of the three connections with continental Italy. Total power consumption variation provided by DSR.

4.3.2.2.4 Outage of Termini Imerese unit G1 and the corresponding BESS

The following Figure 98 and Figure 99 report the simulation results obtained with the outage of Termini Imerese unit G1 and the corresponding BESS (loss of 321 MW of generated power). Frequency stability is guaranteed without using BESSs and DSR since frequency is always higher than the normal operating conditions limit of 49.9 Hz.

Figure 100 shows the power exchanged through the three connections with continental Italy. We can observe that import is increased because of the loss of generation occurring in Sicily.

We verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

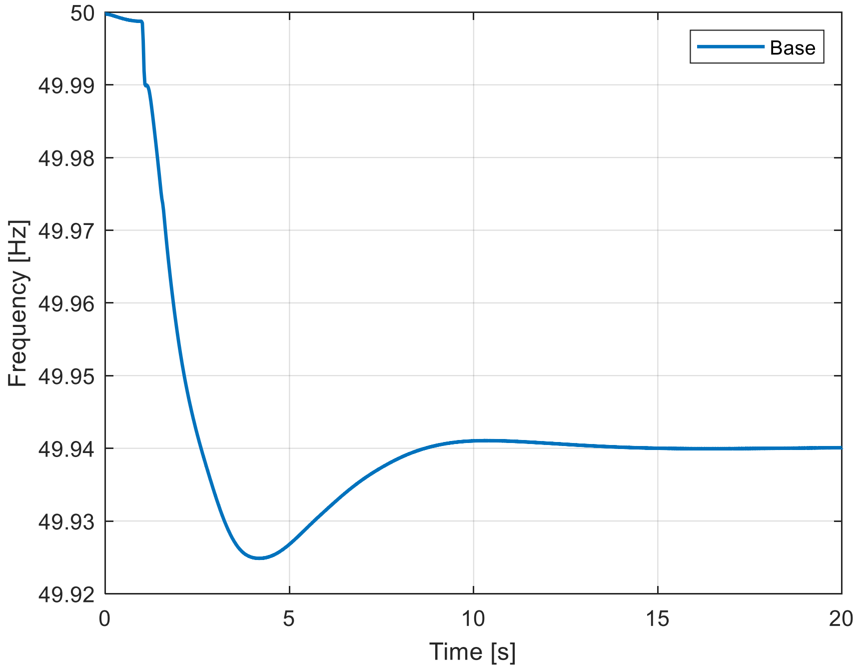

Figure 98. Network: 2050. Dispatching profile: High Import, Event: outage of Termini Imerese unit G1 and the corresponding BESS. Frequency profiles.

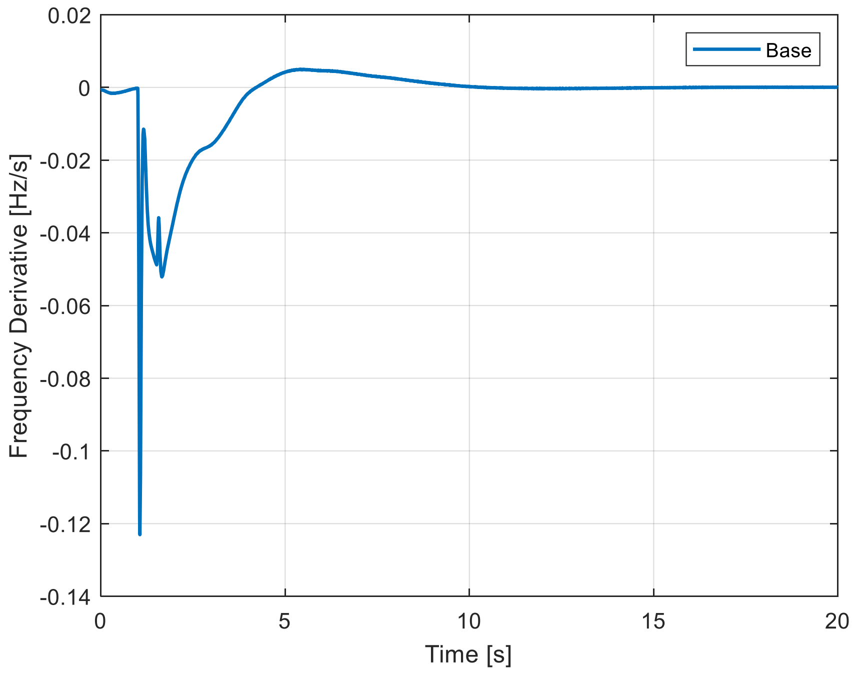

Figure 99. Network: 2050. Dispatching profile: High Import, Event: outage of Termini Imerese unit G1 and the corresponding BESS. Frequency derivative profiles.

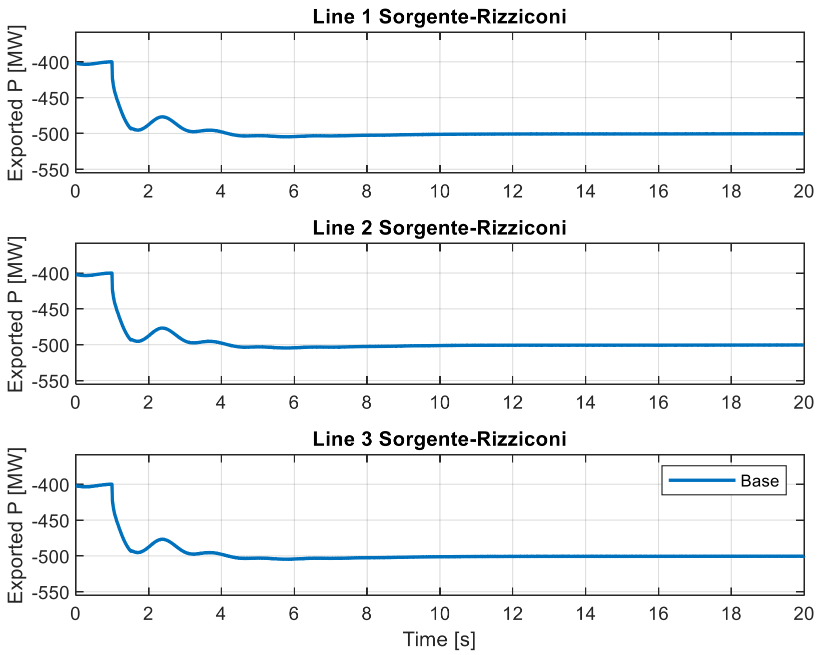

Figure 100. Network: 2050. Dispatching profile: High Import, Event: outage of Termini Imerese unit G1 and the corresponding BESS. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.2.2.5 Outage of Termini Imerese units G1 and G2 and the corresponding BESSs

The following Figure 101 and Figure 102 report the simulation results obtained with the outage of Termini Imerese units G1 and G2 and the corresponding BESSs (loss of 569 MW of generated power). We can observe that without the contribution of DSR and BESSs **the limit of 49.9 Hz for normal operating conditions is violated**. **A total additive reserve of 338 MW, realized with the configuration BESS-3 DSR-25 (see Table 13), is required to keep frequency higher than 49.9 Hz.** In any case, stability is guaranteed also without the support DSR and/or BESSs.

Figure 103 shows the power exchanged through the three connections with continental Italy. We can observe that import is increased because of the loss of generation occurring in Sicily. This variation on the power import is reduced with respect to the base configuration case as higher is the contribution of BESSs and DSR.

Figure 104 shows the active power exchanged by the BESSs associated to in-service traditional generators, FCWT and DFIG plants. In this dispatching profile, BESSs are not exchanging power when simulation starts. Then, when the perturbation occurs, they increase their power export to support the frequency regulation. As expected, the provided power variation is higher as the equivalent droop coefficient is lowered.

Figure 105 reports the variation of the active power absorbed by loads operating DSR. We can observe that, as frequency decreases, the power demand is reduced to support frequency regulation. We can observe also that a sharp and significant variation is provided soon after the event occurrence. This happens because DSR provides a support to synthetic inertia, further than to primary frequency regulation. According to Figure 102, frequency derivative reaches its minimum within the first instants after the event. Therefore, loads immediately response with a sharp decrease of power consumption, proportionally to the frequency derivative.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

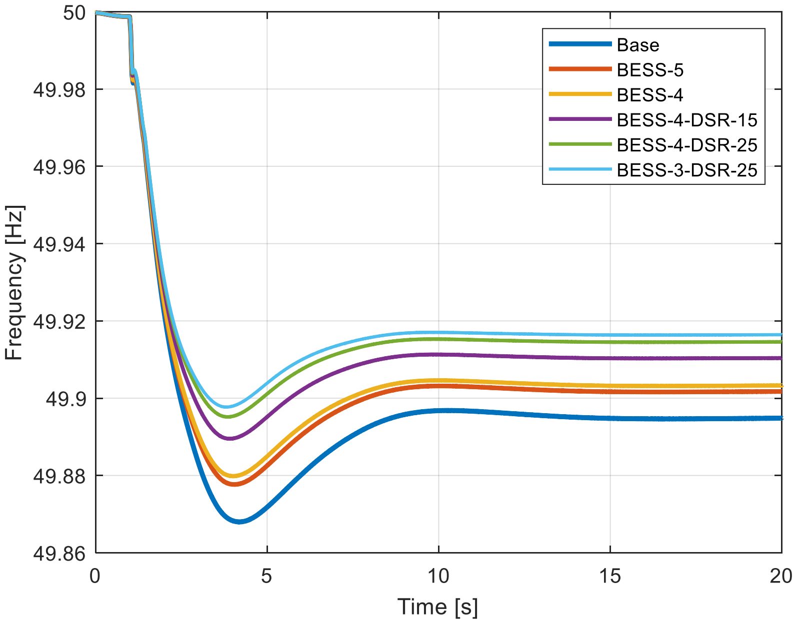

Figure 101. Network: 2050. Dispatching profile: High Import, Event: outage of Termini Imerese units G1 and G2 and the corresponding BESSs. Frequency profiles.

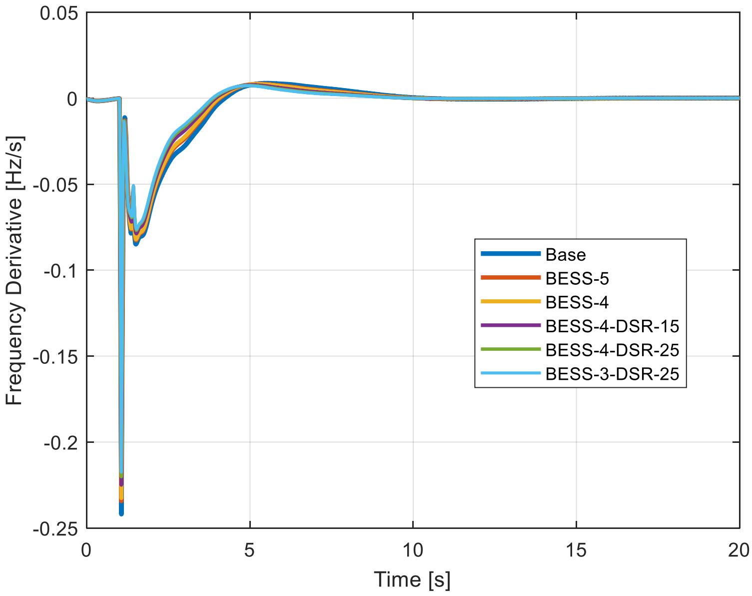

Figure 102. Network: 2050. Dispatching profile: High Import, Event: outage of Termini Imerese units G1 and G2 and the corresponding BESSs. Frequency derivative profiles.

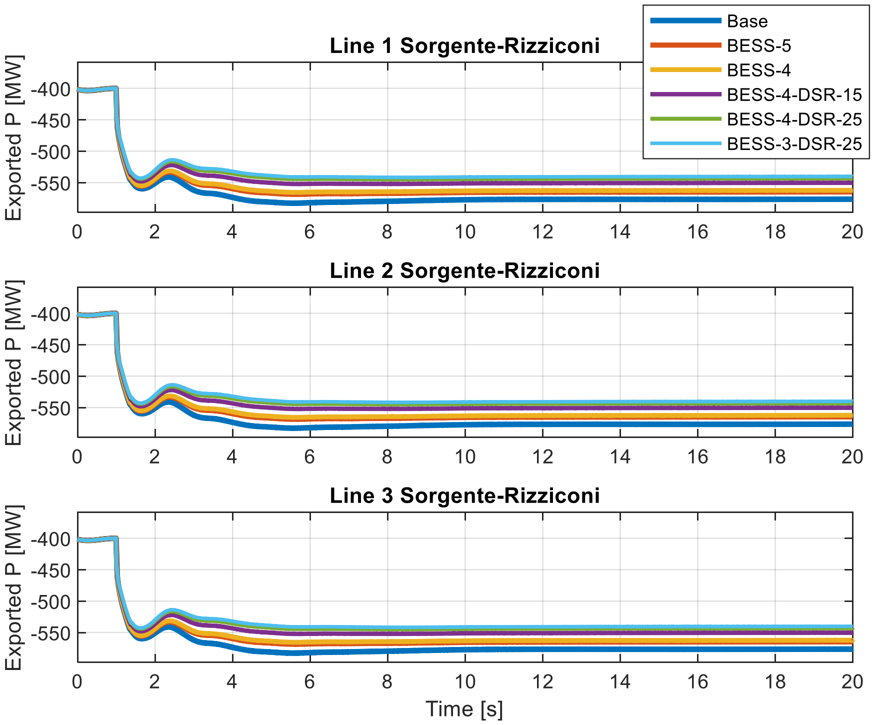

Figure 103. Network: 2050. Dispatching profile: High Import, Event: outage of Termini Imerese units G1 and G2 and the corresponding BESSs. Power exported from the Sorgente terminal through the three connections with continental Italy.

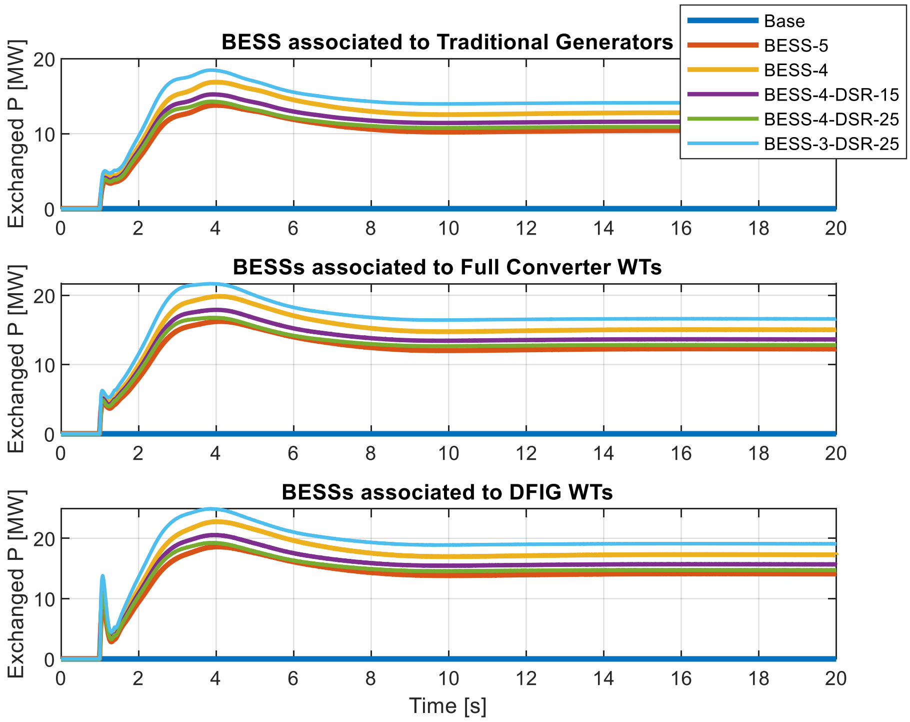

Figure 104. Network: 2050. Dispatching profile: High Import, Event: outage of Termini Imerese units G1 and G2 and the corresponding BESSs. Power exchanged by BESSs (positive means export, negative means import).

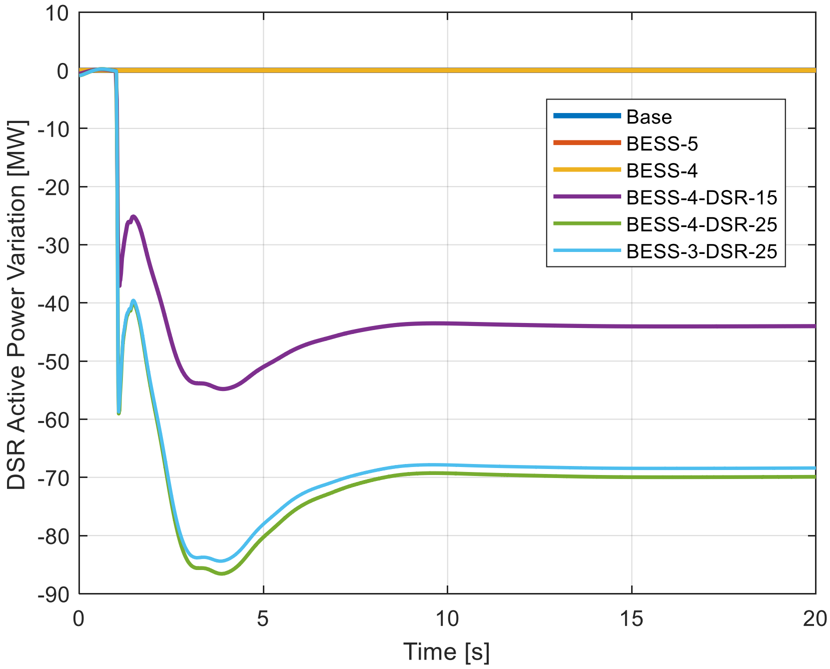

Figure 105. Network: 2050. Dispatching profile: High Import, Event: outage of Termini Imerese units G1 and G2 and the corresponding BESSs. Total power consumption variation provided by DSR.

4.3.2.2.6 Outage of all Termini Imerese units and the corresponding BESSs

The following Figure 106 and Figure 107 report the simulation results obtained with the outage of all Termini Imerese units and the corresponding BESSs (loss of 817 MW of generated power). We can observe that **without the contribution of DSR and BESSs the limit of 49.9 Hz for normal operating conditions is violated**. In this case, **a total additive reserve of 751 MW, realized with the configuration BESS-1 DSR-35 (see Table 13), is sufficient to obtain a steady-state frequency value higher than 49.9 Hz**. However, stability is always guaranteed, also with the base configuration, even if frequency reaches a minimum of about 49.77 Hz. By increasing the contribution of BESSs and DSR such a minimum is increased up to about 49.87 Hz obtained in the mentioned BESS-1 DSR-35 configuration.

Figure 108 shows the power exchanged through the three connections with continental Italy. We can observe that import is increased because of the loss of generation occurring in Sicily. This variation is reduced as higher is the contribution of BESSs and DSR.

Figure 109 shows the active power exchanged by the BESSs associated to in-service traditional generators, FCWT and DFIG plants. In this dispatching profile, BESSs are not exchanging power when simulation starts. Then, when the perturbation occurs, they increase their power export to support the frequency regulation. As expected, the provided power variation is higher as the equivalent droop coefficient is lowered.

Figure 110 reports the variation of the active power absorbed by loads operating DSR. We can observe that, as frequency decreases, the power demand is reduced to support frequency regulation. An initial large decrease of power consumption is registered during the very first instants after the perturbations. This happens because loads provide synthetic inertia. According to Figure 107, frequency derivative reaches its minimum within the first instants after the event. Therefore, loads immediately response with a sharp decrease of power consumption, proportionally to the frequency derivative.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

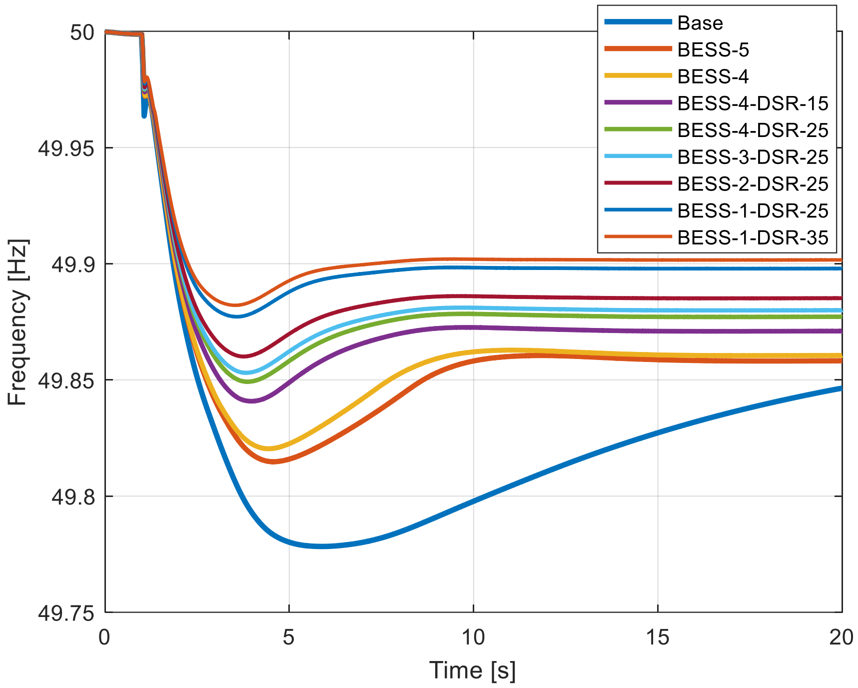

Figure 106. Network: 2050. Dispatching profile: High Import, Event: outage of all Termini Imerese units and the corresponding BESSs. Frequency profiles.

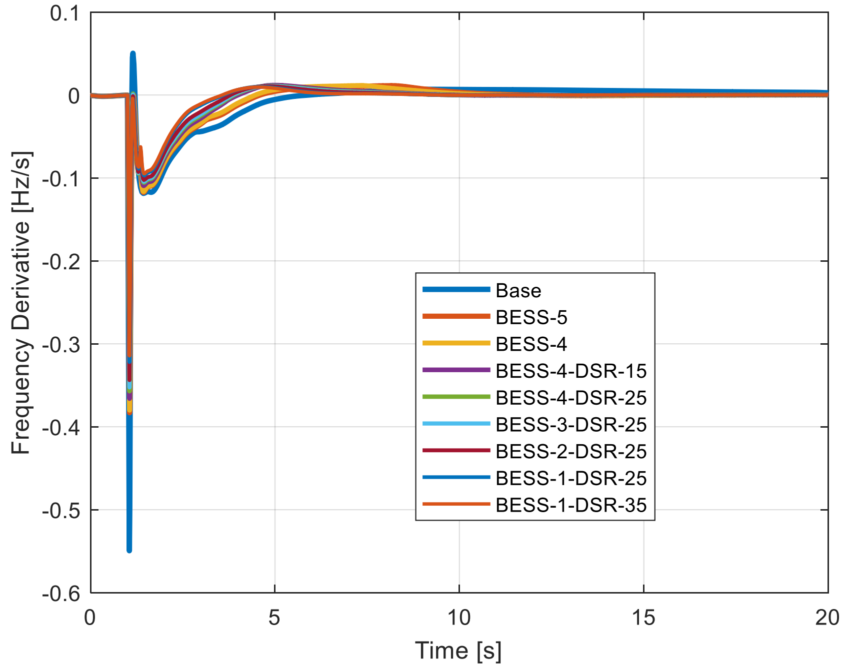

Figure 107. Network: 2050. Dispatching profile: High Import, Event: outage of all Termini Imerese units and the corresponding BESSs. Frequency derivative profiles.

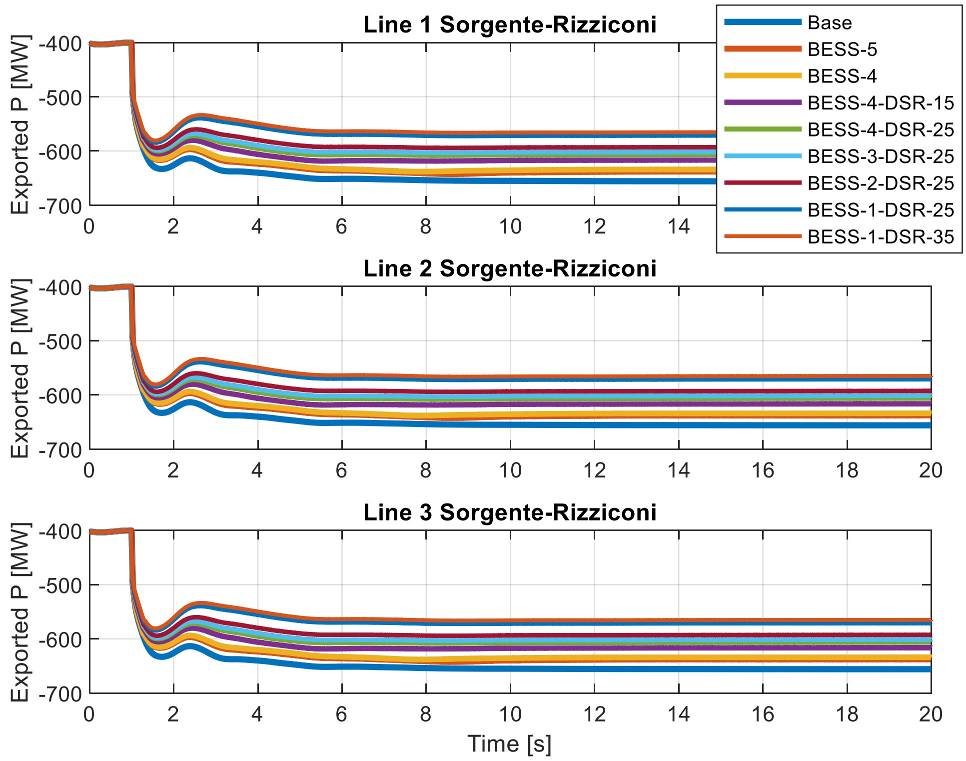

Figure 108. Network: 2050. Dispatching profile: High Import, Event: outage of all Termini Imerese units and the corresponding BESSs. Power exported from the Sorgente terminal through the three connections with continental Italy.

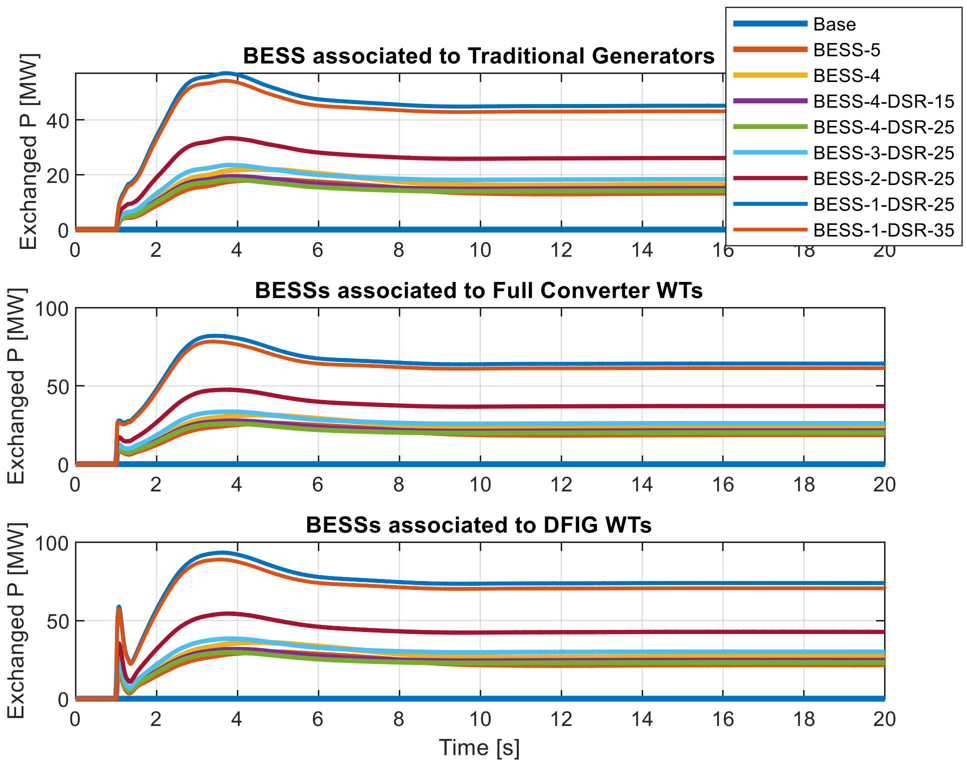

Figure 109. Network: 2050. Dispatching profile: High Import, Event: outage of all Termini Imerese units and the corresponding BESSs. Power exchanged by BESSs (positive means export, negative means import).

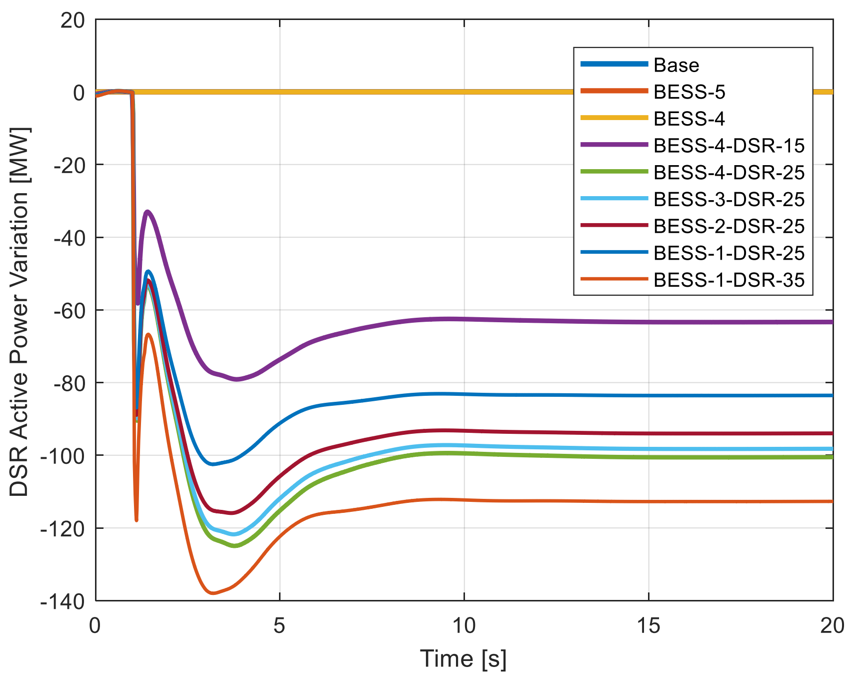

Figure 110. Network: 2050. Dispatching profile: High Import, Event: outage of all Termini Imerese units and the corresponding BESSs. Total power consumption variation provided by DSR.

4.3.2.3 High Load dispatching profile

In this dispatching profile, the events reported in the following have been simulated:

- **load-step occurring in continental Italy:** emulation of the loss of 500 MW of generated power;
- **outage of one of the three connections with continental Italy;**
- **outage of two of the three connections with continental Italy;**
- **outage of all Termini Imerese units (Snom = 946 MVA) and the corresponding BESSs (Snom = 189 MVA):** total loss of 337 MW of injected power.

Here, the only Base configuration has been simulated, since no stability problems have been detected.

The following figures from Figure 111 to Figure 122 report the results obtained according to the four simulated events. It can be observed that, also thanks to the high level of traditional and wind generation in service, no critical frequency deviations occur. Therefore, **the support BESSs and DSR is not necessary**.

4.3.2.3.1 Load-step in continental Italy

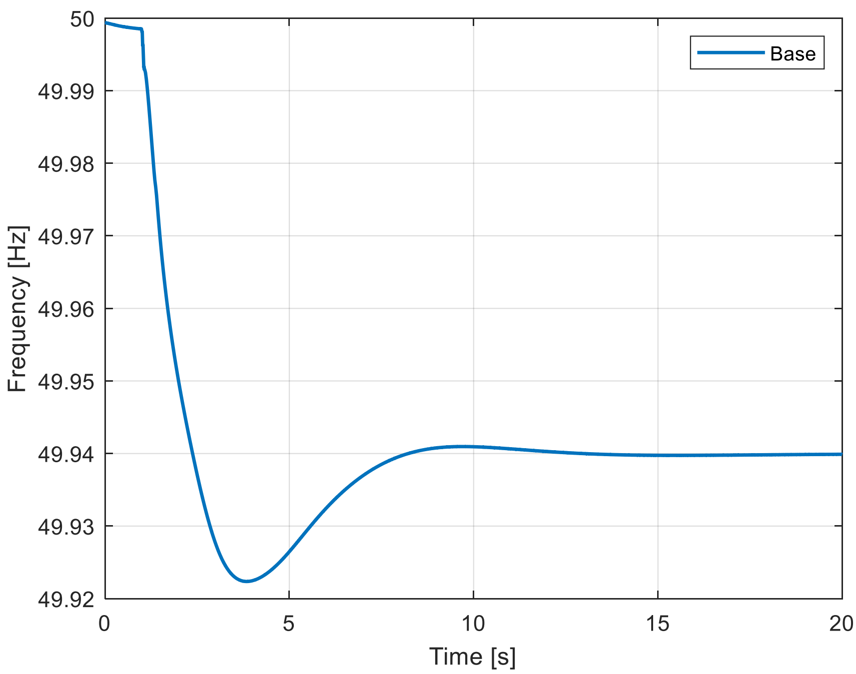

Figure 111. Network: 2050. Dispatching profile: High Load, Event: load-step in continental Italy. Frequency profiles.

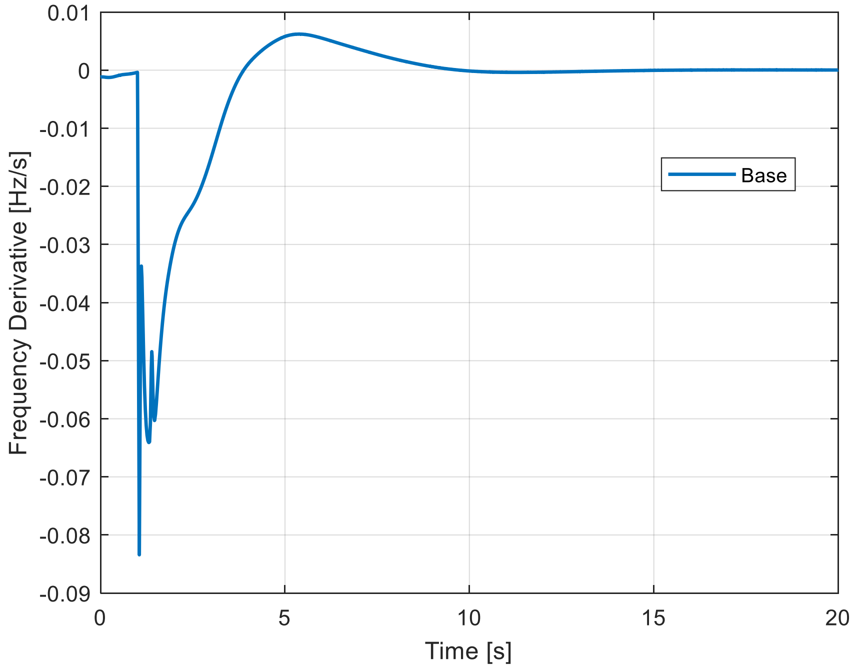

Figure 112. Network: 2050. Dispatching profile: High Load, Event: load-step in continental Italy. Frequency derivative profiles.

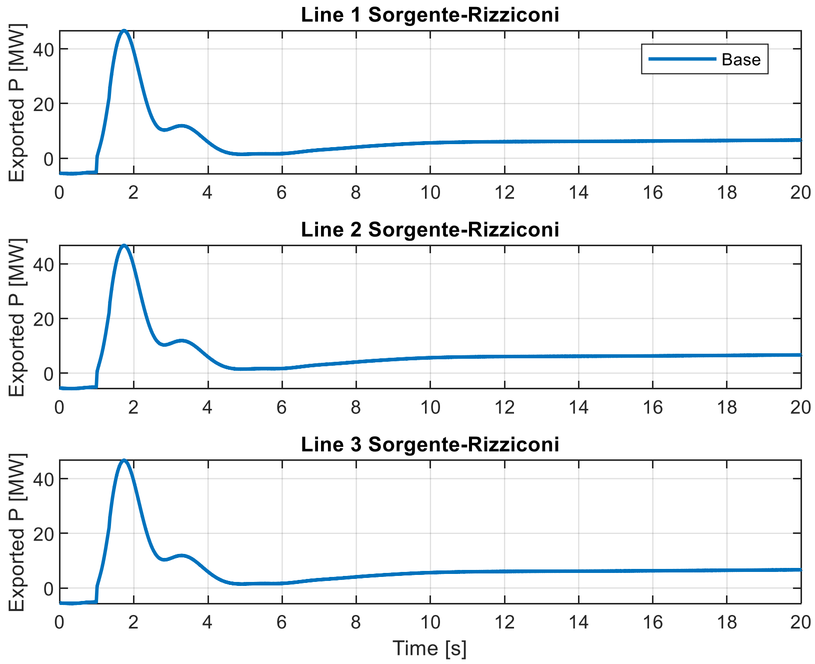

Figure 113. Network: 2050. Dispatching profile: High Load, Event: load-step in continental Italy. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.2.3.2 Outage of one of the three connections with continental Italy

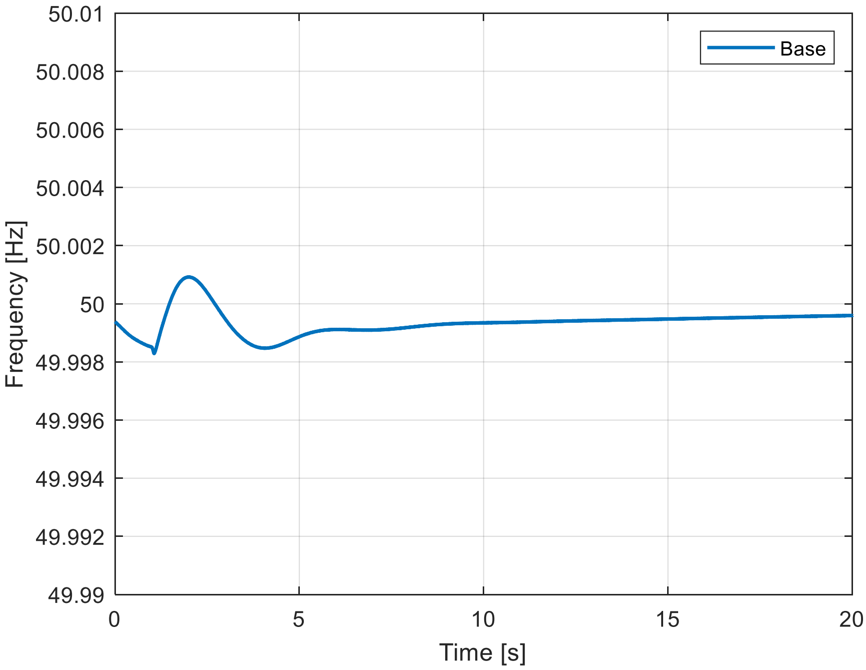

Figure 114. Network: 2050. Dispatching profile: High Load, Event: outage of one of the three connections with continental Italy. Frequency profiles.

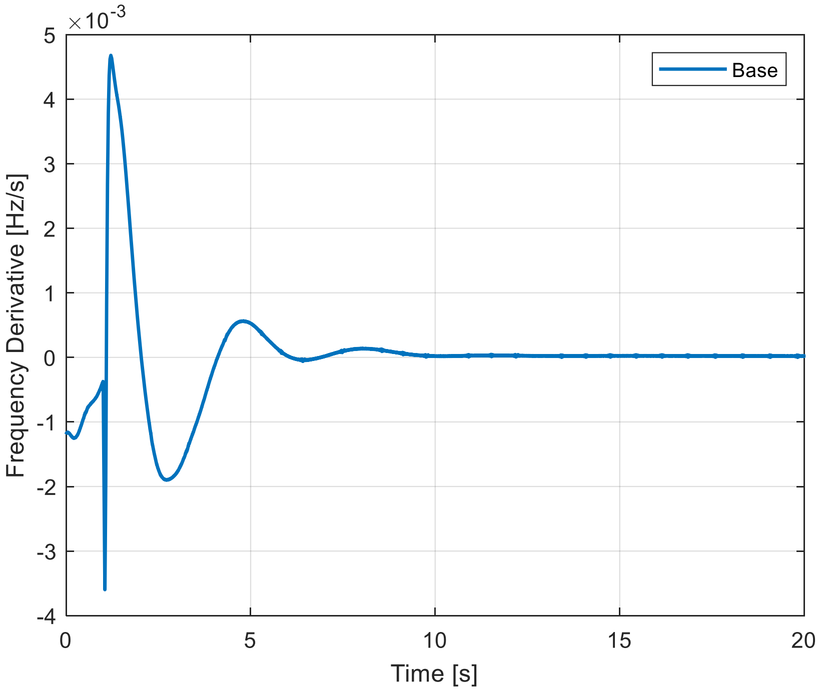

Figure 115. Network: 2050. Dispatching profile: High Load, Event: outage of one of the three connections with continental Italy. Frequency derivative profiles.

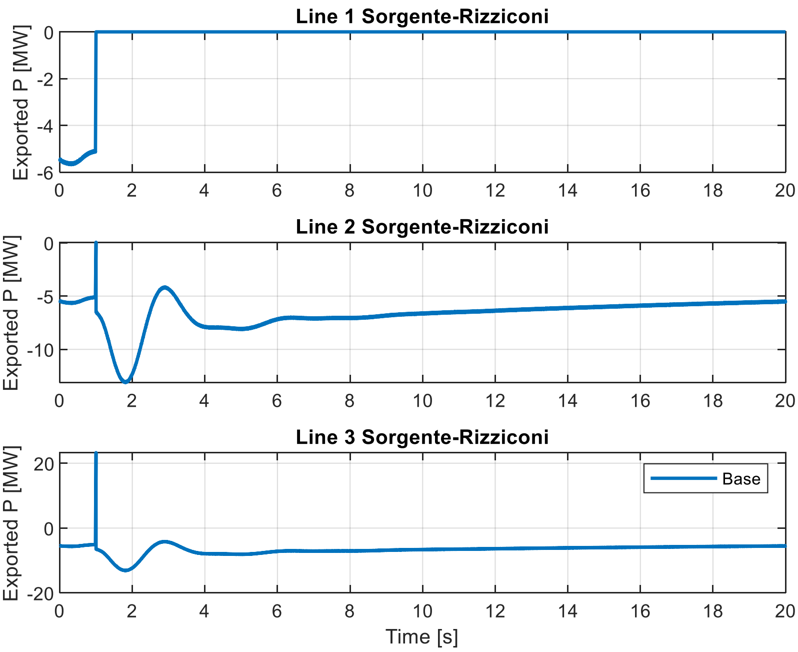

Figure 116. Network: 2050. Dispatching profile: High Load, Event: outage of one of the three connections with continental Italy. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.2.3.3 Outage of two of the three connections with continental Italy

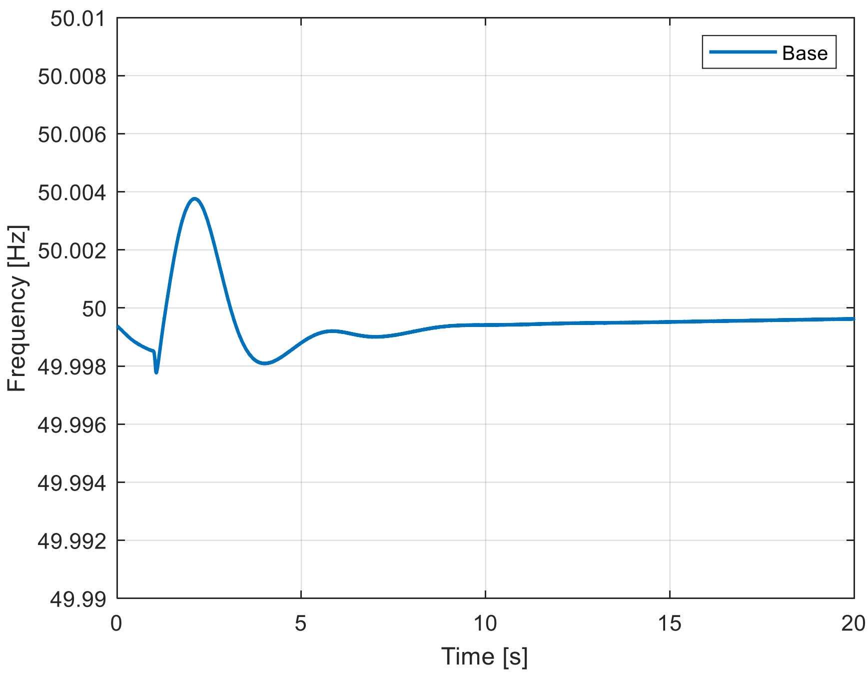

Figure 117. Network: 2050. Dispatching profile: High Load, Event: outage of two of the three connections with continental Italy. Frequency profiles.

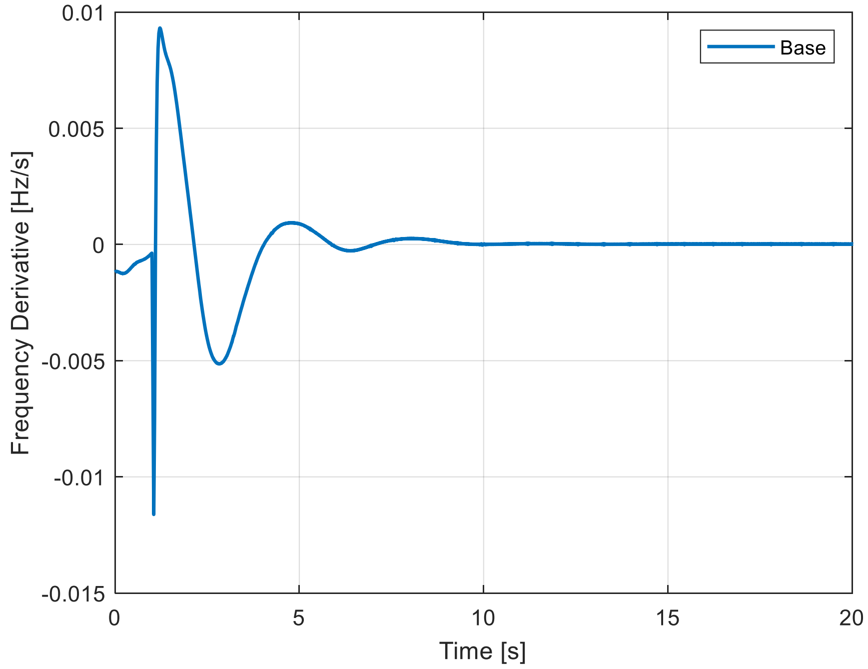

Figure 118. Network: 2050. Dispatching profile: High Load, Event: outage of two of the three connections with continental Italy. Frequency derivative profiles.

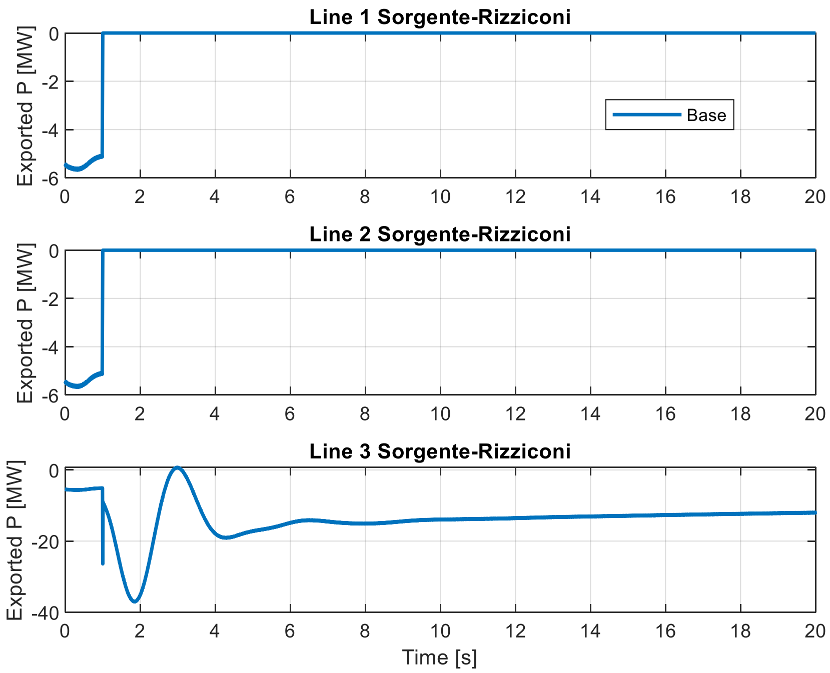

Figure 119. Network: 2050. Dispatching profile: High Load, Event: outage of two of the three connections with continental Italy. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.2.3.4 Outage of all Termini Imerese units and the corresponding BESSs

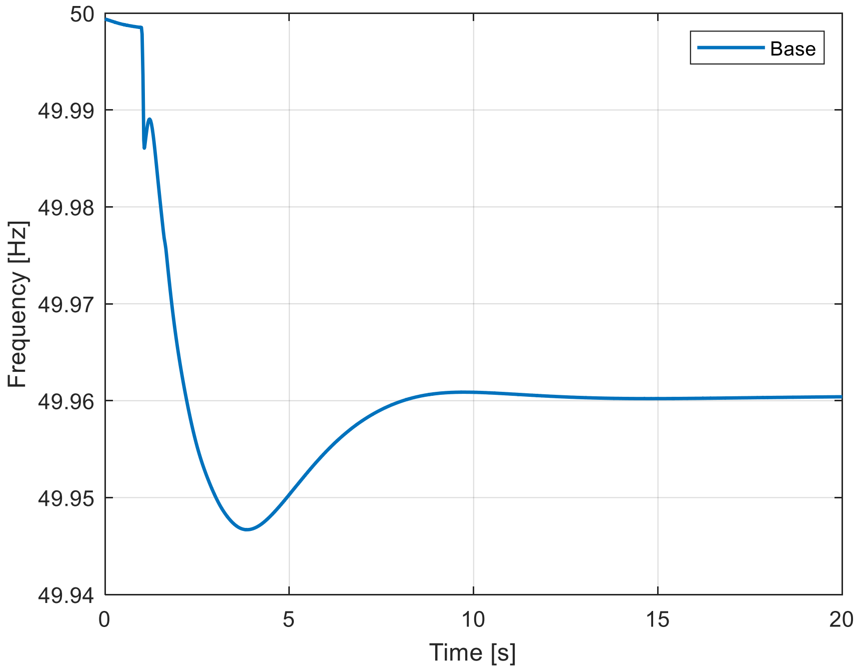

Figure 120. Network: 2050. Dispatching profile: High Load, Event: outage of all Termini Imerese units and the corresponding BESSs. Frequency profiles.

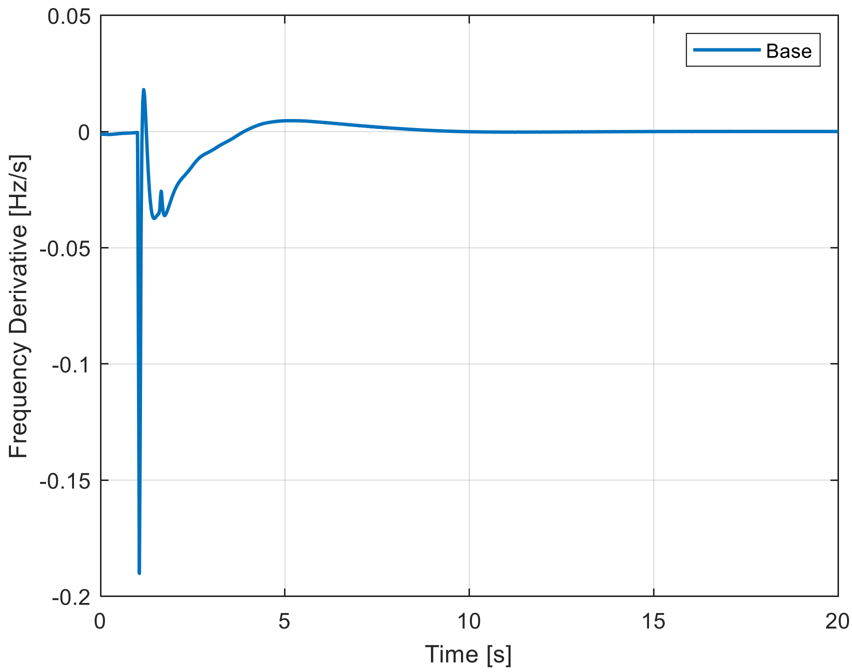

Figure 121. Network: 2050. Dispatching profile: High Load, Event: outage of all Termini Imerese units and the corresponding BESSs. Frequency derivative profiles.

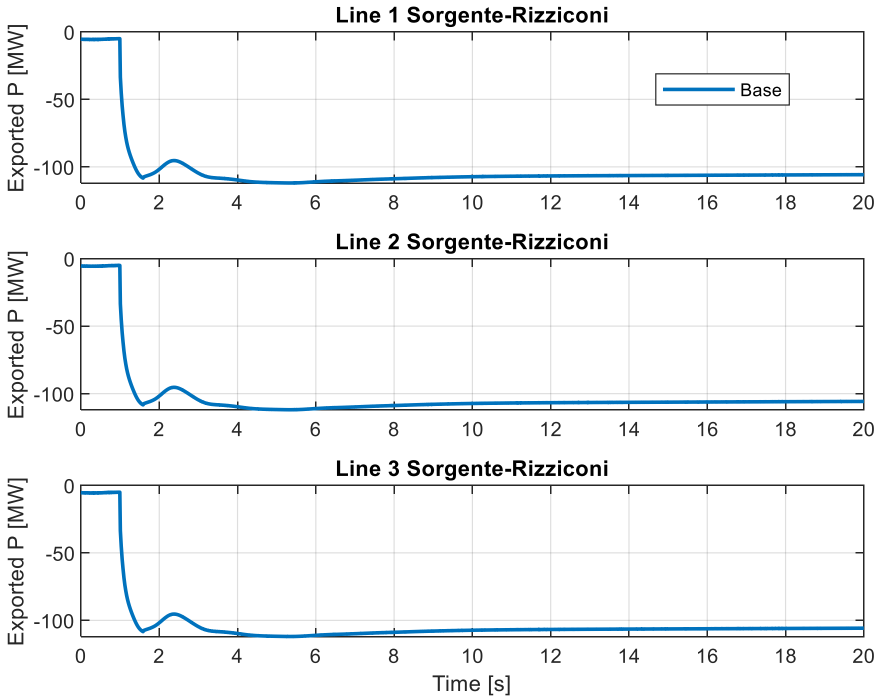

Figure 122. Network: 2050. Dispatching profile: High Load, Event: outage of all Termini Imerese units and the corresponding BESSs. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.2.4 Island dispatching profile

In this dispatching profile, the events reported in the following have been simulated:

- outage of all Termini Imerese units (Snom = 946 MVA) and the corresponding BESSs (Snom = 189 MVA): total loss of 337 MW of injected power.

The DSR and BESS FCR network configurations listed in Table 14 have been considered.

Network Configuration	K_{BESS}^{tot} [MW]	K_{DSR}^{tot} [MW]	K^{tot} [MW]	% DSR	% Loads Operating 5 % DSR	% Loads Operating 10 % DSR
BESS-3	174	0	174	0 %	0 %	0 %
BESS-1	520	0	520	0 %	0 %	0 %
BESS-1 DSR-20	520	166	686	4 %	77 %	39 %

*Total Load = 4294 MW

Table 14. Network 2050. Dispatching profile: Island. DSR/BESS FCR network configuration parameters.

4.3.2.4.1 Outage of all Termini Imerese units and the corresponding BESSs

The following Figure 123 and Figure 124 report the simulation results obtained with the outage of all Termini Imerese units and the corresponding BESSs (loss of 337 MW of generated power). We can observe that **without the contribution of DSR and BESSs the limit of 49.5 Hz for normal operating conditions in islanded mode is violated**. In this case, a total additive reserve of 174 MW, realized with the configuration BESS-3, is sufficient to keep frequency higher than the mentioned threshold. With a total additive reserve of 868 MW, realized with the configuration BESS-1 DSR-20 (see Table 14), frequency deviation is further limited with a steady-state value slightly lower than 49.9 Hz. In any case, stability is guaranteed also without the support DSR and/or BESSs.

Figure 125 shows the active power exchanged by the BESSs associated to in-service traditional generators, FCWT and DFIG plants. Moreover, BESSs are not exchanging power when simulation starts. Then, when the perturbation occurs, they increase their power export to support the frequency regulation. As expected, the provided power variation is higher as the equivalent droop coefficient is lowered.

Figure 126 reports the variation of the active power absorbed by loads operating DSR. We can observe that, as frequency decreases, the power demand is reduced to support frequency regulation. We can observe that a sharp and significant variation is provided soon after the event occurrence. This happens because DSR provides a support to synthetic inertia, further than to primary frequency regulation. According to Figure 124, frequency derivative reaches its minimum within the first instants after the event. Therefore, loads immediately response with a sharp decrease of power consumption, proportionally to the frequency derivative.

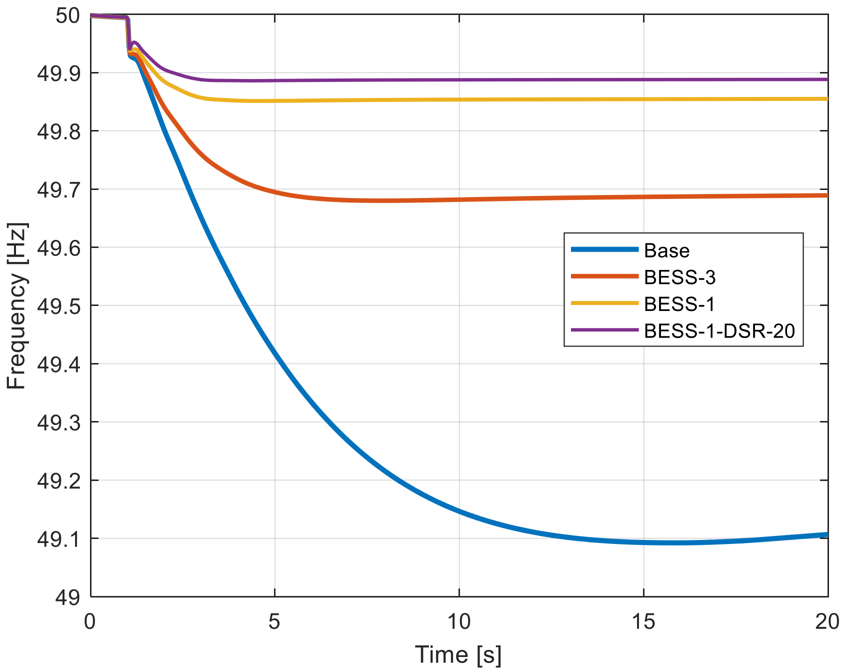

Figure 123. Network: 2050. Dispatching profile: Island, Event: outage of all Termini Imerese units and the corresponding BESSs. Frequency profiles.

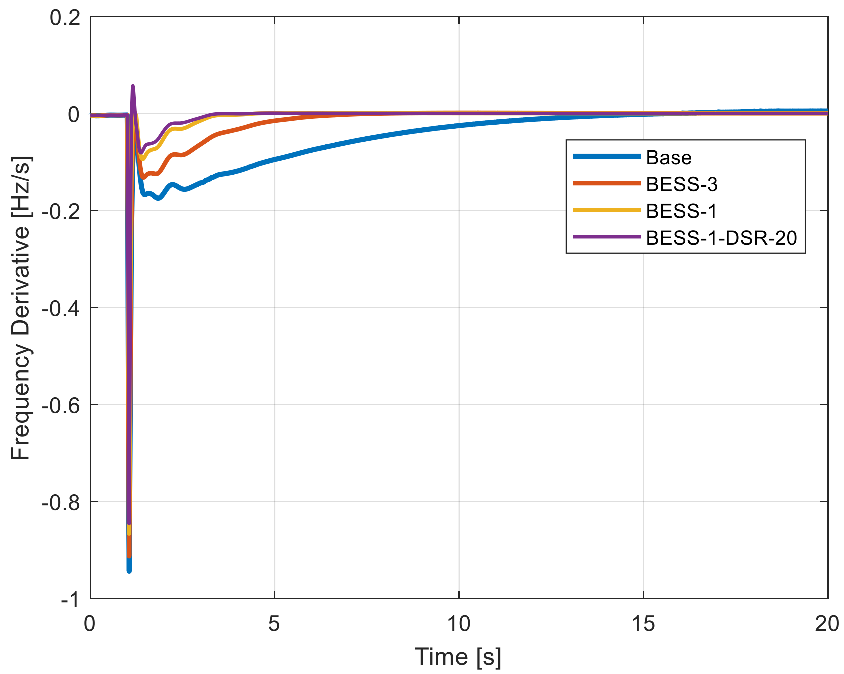

Figure 124. Network: 2050. Dispatching profile: Island, Event: outage of all Termini Imerese units and the corresponding BESSs. Frequency derivative profiles.

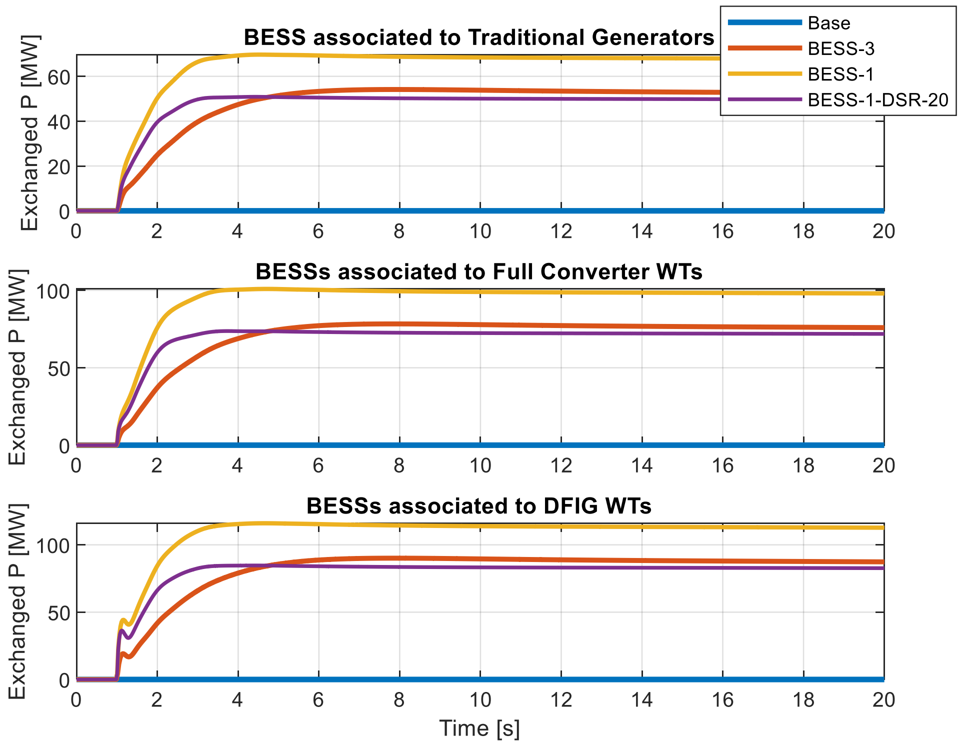

Figure 125. Network: 2050. Dispatching profile: Island, Event: outage of all Termini Imerese units and the corresponding BESSs. Power exchanged by BESSs (positive means export, negative means import).

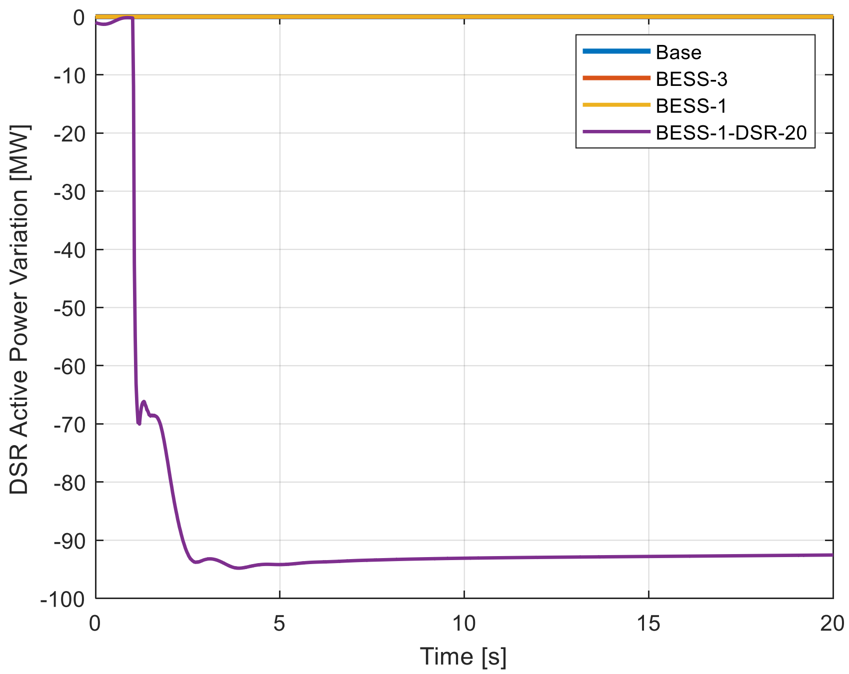

Figure 126. Network: 2050. Dispatching profile: Island, Event: outage of all Termini Imerese units and the corresponding BESSs. Total power consumption variation provided by DSR.

4.3.2.5 Low Load dispatching profile

In this dispatching profile, the events reported in the following have been simulated:

- **load-step occurring in continental Italy:** emulation of the loss of 500 MW of generated power;
- **outage of one of the three connections with continental Italy;**
- **outage of two of the three connections with continental Italy;**
- **outage of all Termini Imerese units (Snom = 946 MVA) and the corresponding BESSs (Snom = 189 MVA):** total loss of 337 MW of injected power.

The DSR and BESS FCR network configurations listed in Table 15 have been considered.

Network Configuration	K_{BESS}^{tot} **[MW]**	K_{DSR}^{tot} **[MW]**	K^{tot} **[MW]**	**% DSR**	**% Loads Operating 5 % DSR**	**% Loads Operating 10 % DSR**
BESS-5	59	0	59	0 %	0 %	0 %
BESS-3	98	0	98	0 %	0 %	0 %
BESS-1	292	0	292	0 %	0 %	0 %
BESS-1 DSR-30	292	70	362	5 %	92 %	46 %
BESS-1 DSR-50	292	116	408	8 %	153 %	77 %

*Total Load = 1514 MW

Table 15. Network 2050. Dispatching profile: Low Load. DSR/BESS FCR network configuration parameters.

4.3.2.5.1 Load-step in continental Italy

The following Figure 127 and Figure 128 report the simulation results obtained with the 500 MW load-step in continental Italy. We can observe that **without the contribution of DSR and BESSs, the limit of 49.9 Hz for normal operating conditions is violated**. A total additive reserve of 362 MW, realized with the configuration BESS-1 DSR-30 (see Table 15), is required to keep frequency higher than 49.9 Hz. In any case, stability is guaranteed also without the support DSR and/or BESSs.

Figure 129 shows the power exchanged through the three connections with continental Italy. Sicily is importing power when simulation starts, then, when the load-step occurs, import is reduced to support the frequency regulation. We can observe how the contribution to regulation provided from Sicily increases as the BESSs droop coefficient decreases and the percentage of loads operating DSR increases.

Figure 130 shows the active power exchanged by the BESSs associated to in-service traditional generators, FCWT and DFIG plants. Moreover, BESSs are not exchanging power when simulation starts. Since all DFIG plants are out of service, also the corresponding BESSs are all out of service. When the perturbation occurs, in-service BESSs increase their power export to support the frequency regulation. As expected, the provided power variation is higher as lower is the droop coefficient.

Figure 131 reports the variation of the active power absorbed by loads operating DSR. We can observe that, as frequency decreases, the power demand is reduced to support frequency regulation. Clearly, the contribution of loads is higher as higher is the percentage of participating loads.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

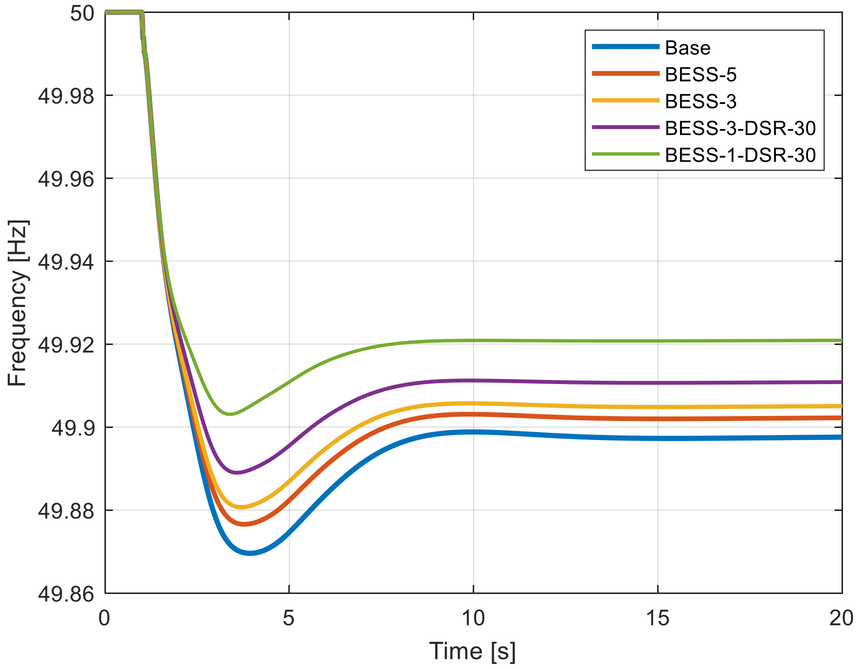

Figure 127. Network: 2050. Dispatching profile: Low Load, Event: load-step in continental Italy. Frequency profiles.

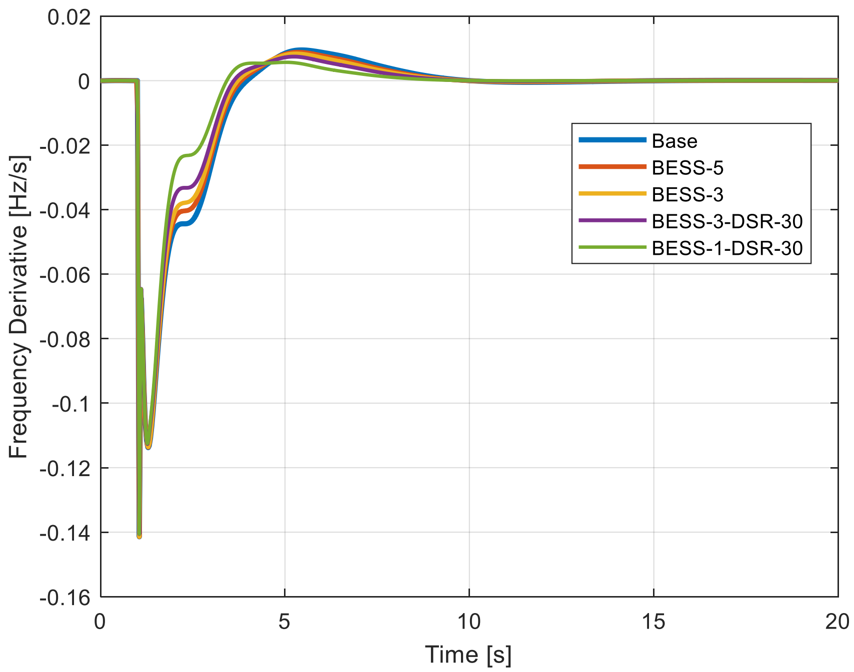

Figure 128. Network: 2050. Dispatching profile: Low Load, Event: load-step in continental Italy. Frequency derivative profiles.

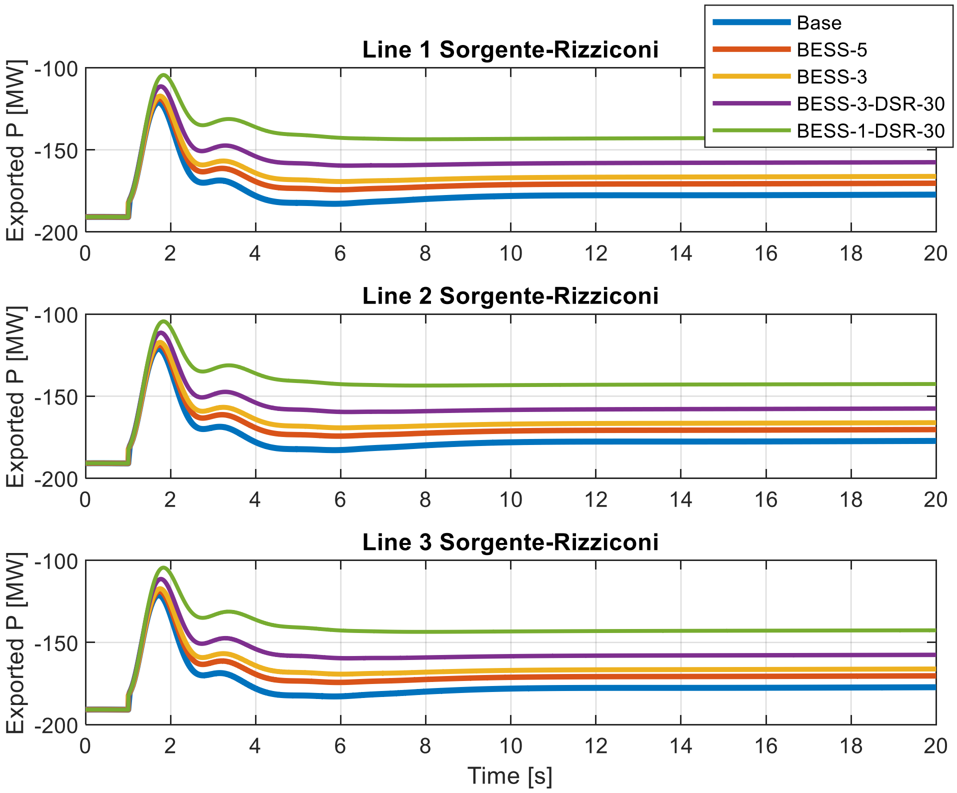

Figure 129. Network: 2050. Dispatching profile: Low Load, Event: load-step in continental Italy. Power exported from the Sorgente terminal through the three connections with continental Italy.

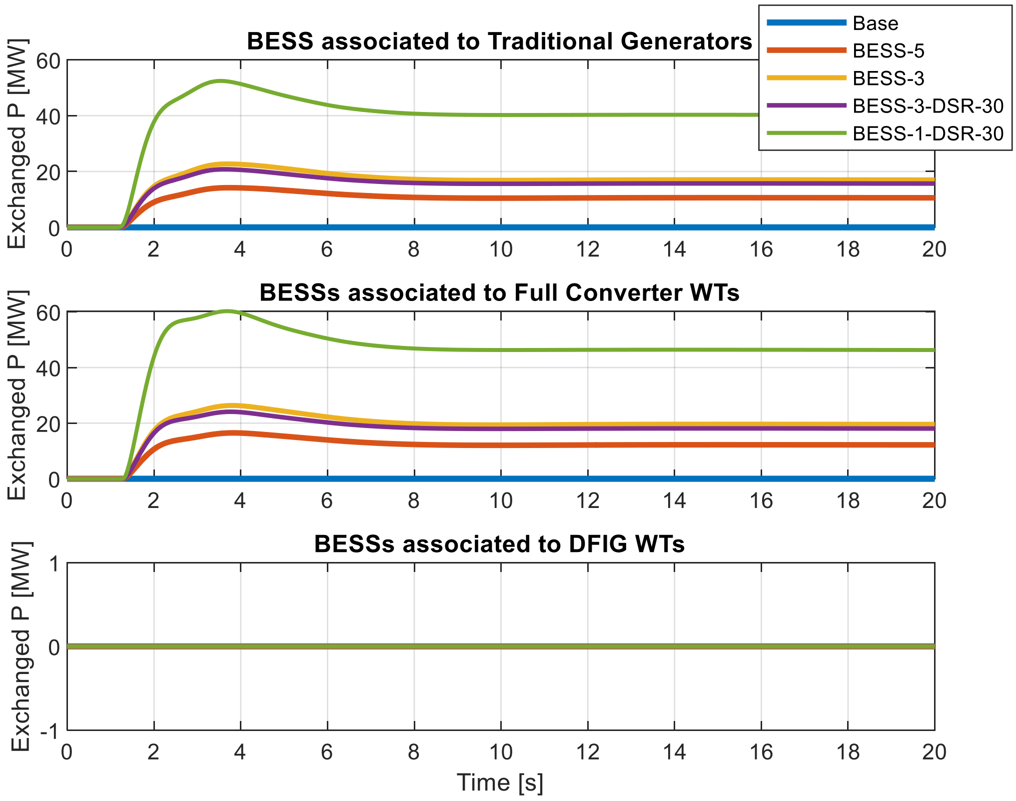

Figure 130. Network: 2050. Dispatching profile: Low Load, Event: load-step in continental Italy. Power exchanged by BESSs (positive means export, negative means import).

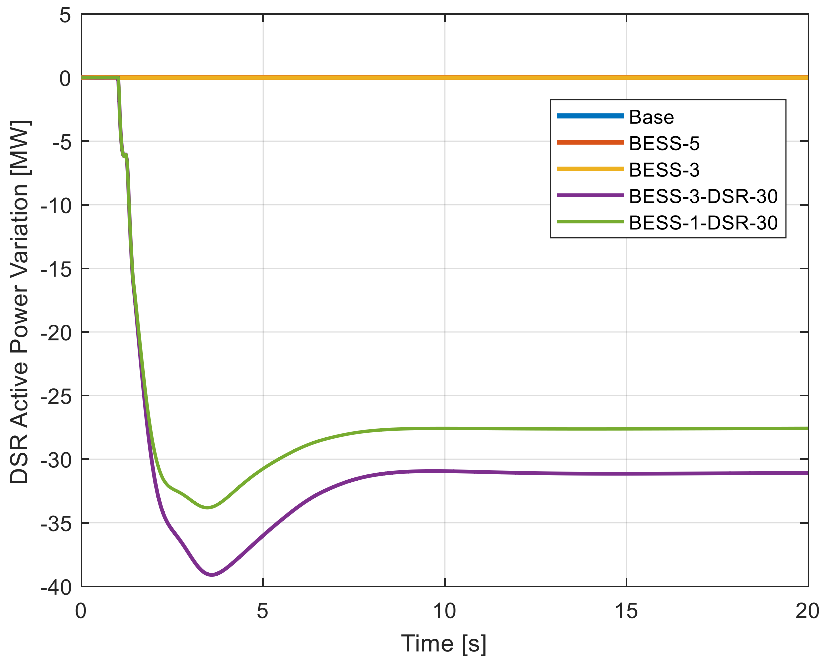

Figure 131. Network: 2050. Dispatching profile: Low Load, Event: load-step in continental Italy. Total power consumption variation provided by DSR.

4.3.2.5.2 Outage of one of the three connections with continental Italy

The following Figure 132 and Figure 133 report the simulation results obtained with the loss of one of the three connections with continental Italy. It can be observed that **frequency stability is guaranteed without using BESSs and DSR**.

Figure 134 shows the power exchanged through the three connections with continental Italy. We can observe that the power exported by the lost connection is distributed to the two remaining connections.

We verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

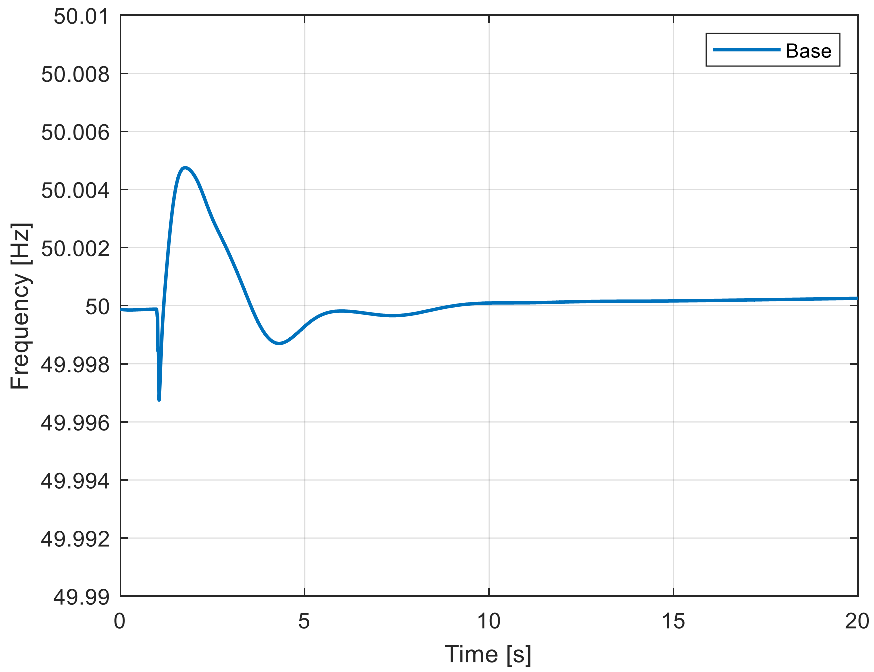

Figure 132. Network: 2050. Dispatching profile: Low Load, Event: outage of one of the three connections with continental Italy. Frequency profiles.

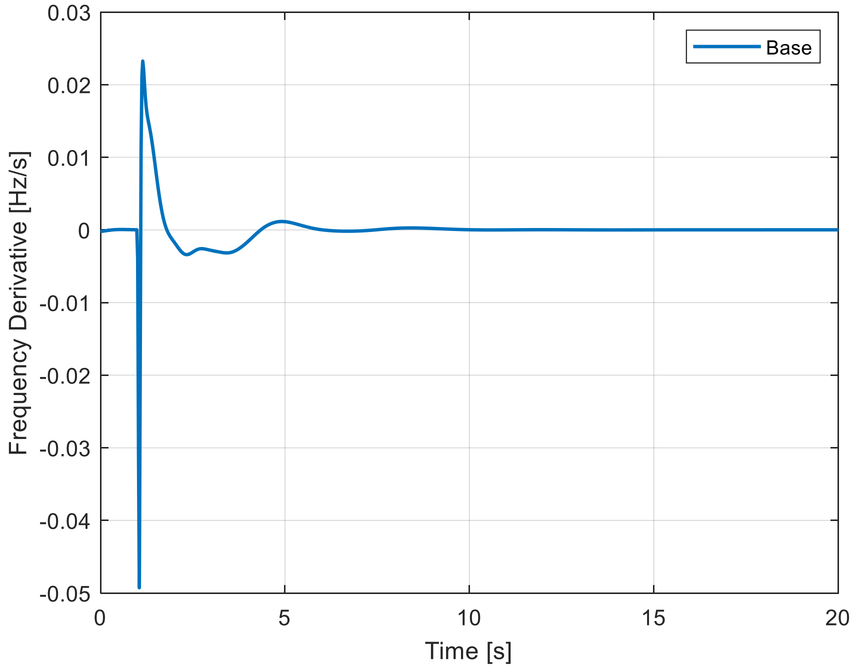

Figure 133. Network: 2050. Dispatching profile: Low Load, Event: outage of one of the three connections with continental Italy. Frequency derivative profiles.

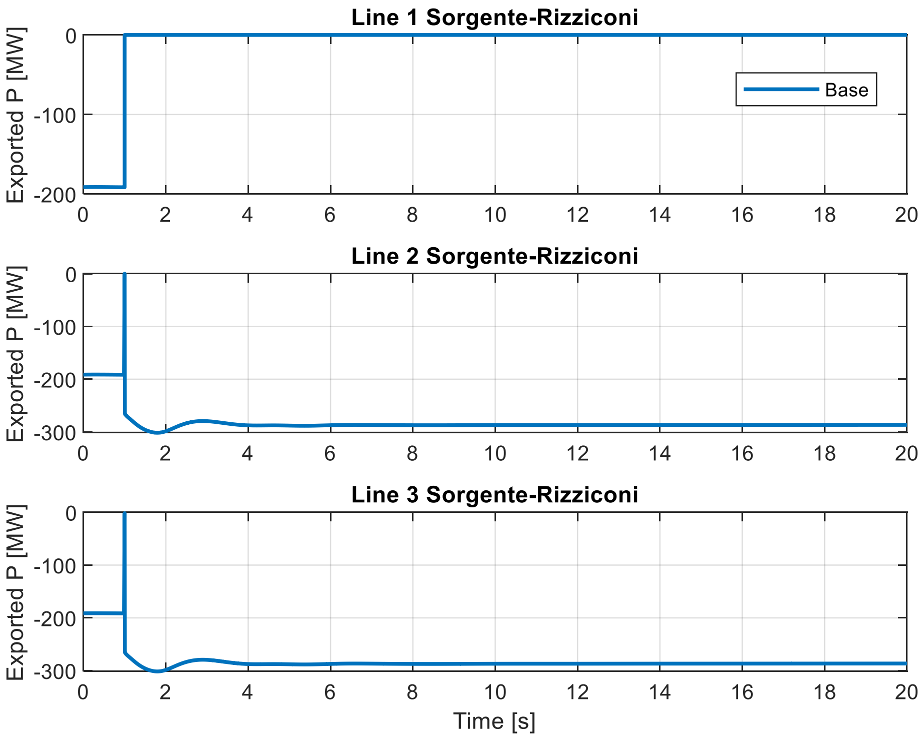

Figure 134. Network: 2050. Dispatching profile: Low Load, Event: outage of one of the three connections with continental Italy. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.2.5.3 Outage of two of the three connections with continental Italy

The following Figure 135 and Figure 136 report the simulation results obtained with the loss of two of the three connections with continental Italy. It can be observed that **frequency stability is guaranteed without using BESSs and DSR**.

Figure 137 shows the power exchanged through the three connections with continental Italy. We can observe that the power imported by the two lost connections is covered by the third connection.

We verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

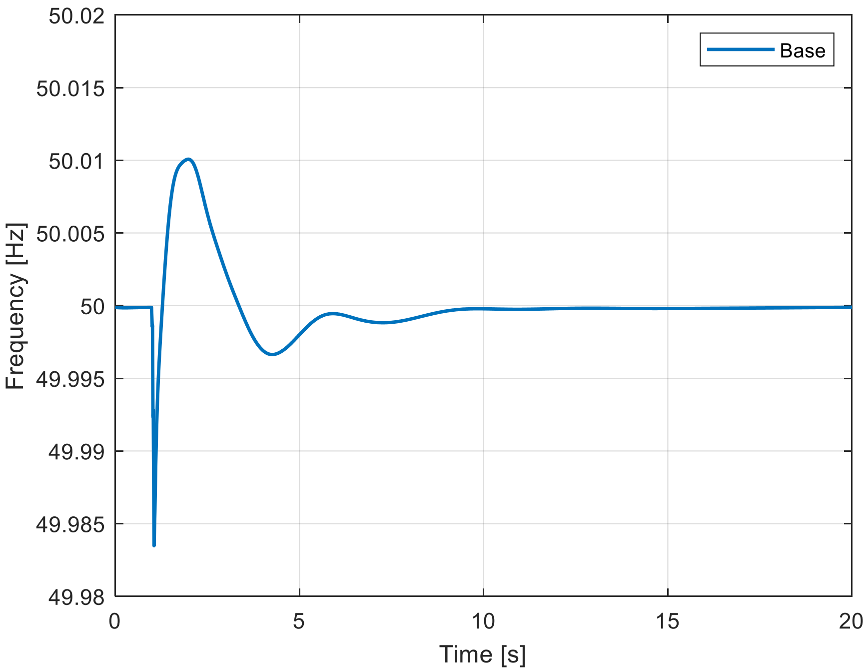

Figure 135. Network: 2050. Dispatching profile: Low Load, Event: outage of two of the three connections with continental Italy. Frequency profiles.

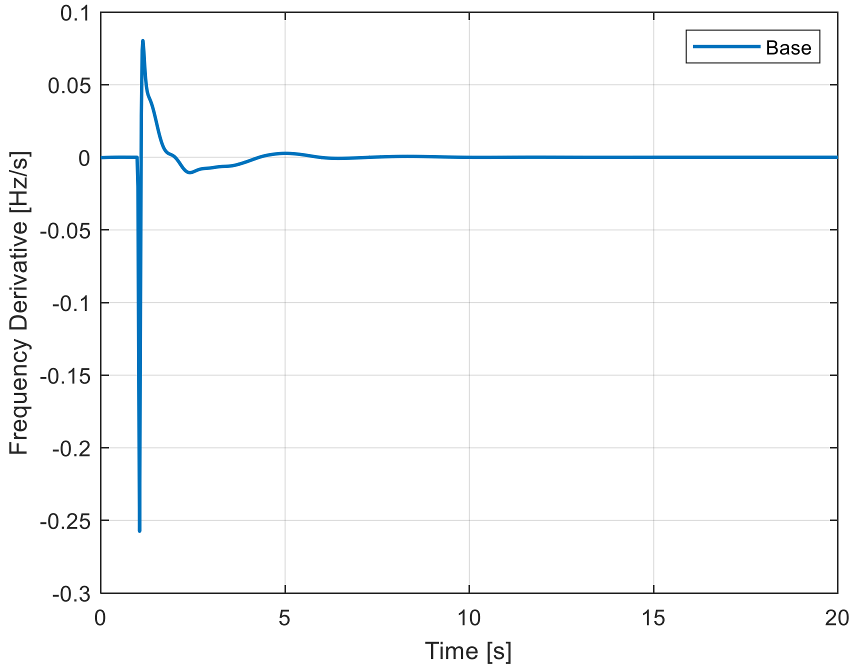

Figure 136. Network: 2050. Dispatching profile: Low Load, Event: outage of two of the three connections with continental Italy. Frequency derivative profiles.

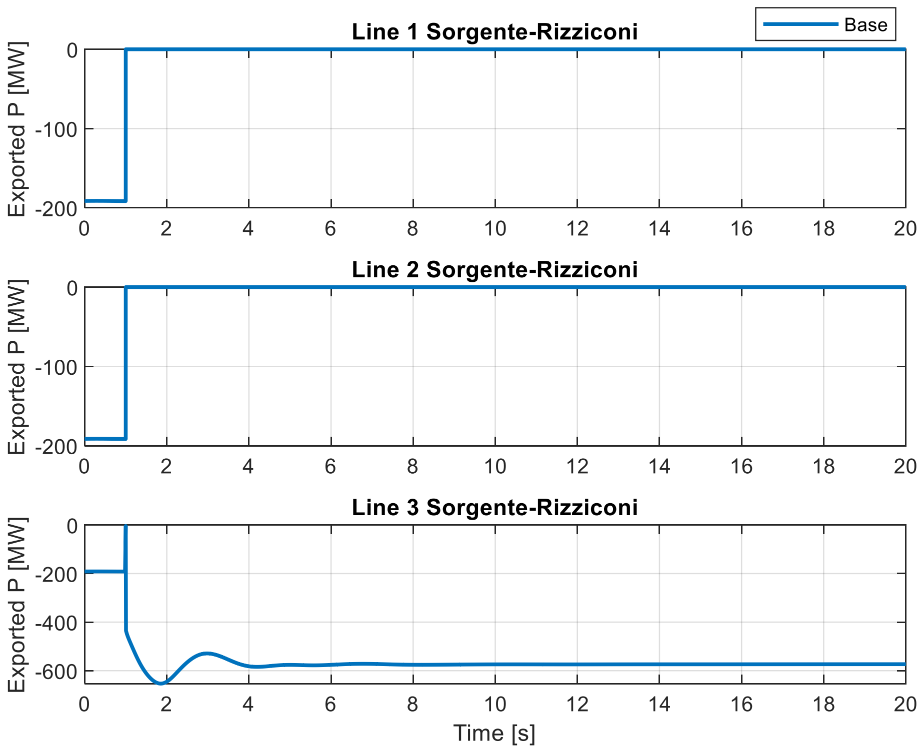

Figure 137. Network: 2050. Dispatching profile: Low Load, Event: outage of two of the three connections with continental Italy. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.2.5.4 Outage of all Termini Imerese units and the corresponding BESSs

The following Figure 138 and Figure 139 report the simulation results obtained with the outage of all Termini Imerese units and the corresponding BESSs (loss of 337 MW of generated power). We can observe that **without the contribution of DSR and BESSs the limit of 49.9 Hz for normal operating conditions is violated**. In this case, **a total additive reserve of 362 MW, realized with the configuration BESS-3 DSR-30 (see Table 15), is sufficient to keep frequency higher than 49.9 Hz**. Notice that also with the configuration BESS-1, frequency is kept higher than 49.9 Hz. In any case, stability is always guaranteed, also with the base configuration.

Figure 140 shows the power exchanged through the three connections with continental Italy. We can observe that import is increased because of the loss of generation occurring in Sicily. This variation is reduced as higher is the contribution of BESSs and DSR.

Figure 141 shows the active power exchanged by the BESSs associated to in-service traditional generators, FCWT and DFIG plants. Moreover, BESSs are not exchanging power when simulation starts. Since all DFIG plants are out of service, also the corresponding BESSs are all out of service. When the perturbation occurs, in-service BESSs increase their power export to support the frequency regulation. As expected, the provided power variation is higher as lower is the droop coefficient.

Figure 142 reports the variation of the active power absorbed by loads operating DSR. We can observe that, as frequency decreases, the power demand is reduced to support frequency regulation. An initial large decrease of power consumption is registered during the very first instants after the perturbations. This happens because loads provide synthetic inertia. According to Figure 139, frequency derivative reaches its minimum within the first instants after the event. Therefore, loads immediately response with a sharp decrease of power consumption, proportionally to the frequency derivative.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

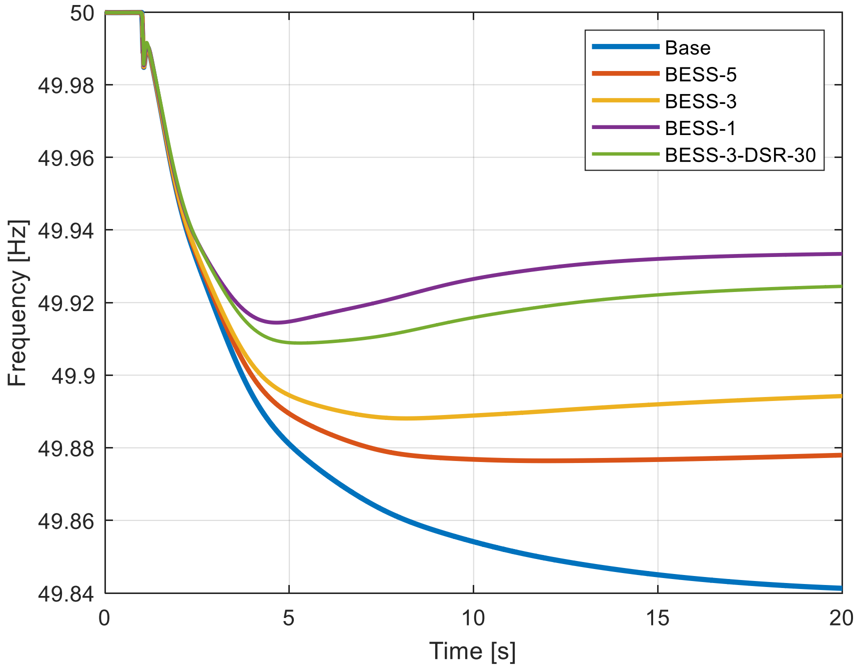

Figure 138. Network: 2050. Dispatching profile: Low Load, Event: outage of all Termini Imerese units and the corresponding BESSs. Frequency profiles.

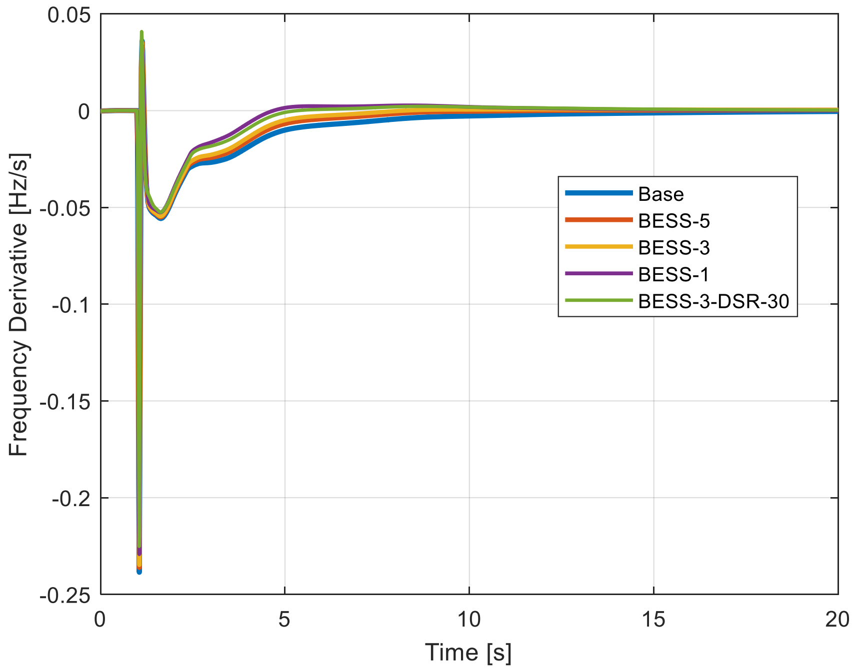

Figure 139. Network: 2050. Dispatching profile: Low Load, Event: outage of all Termini Imerese units and the corresponding BESSs. Frequency derivative profiles.

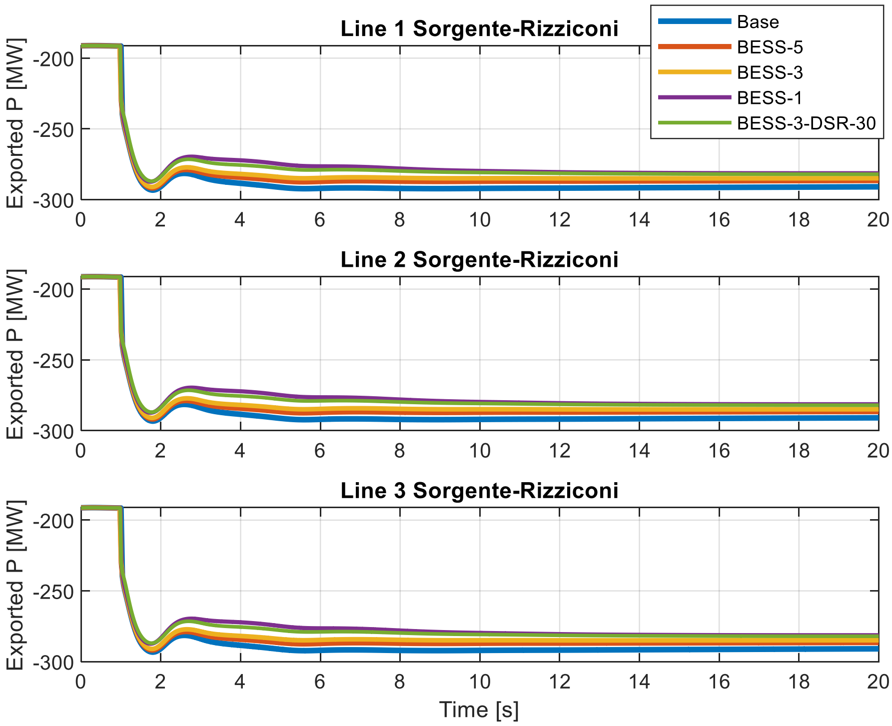

Figure 140. Network: 2050. Dispatching profile: Low Load, Event: outage of all Termini Imerese units and the corresponding BESSs. Power exported from the Sorgente terminal through the three connections with continental Italy.

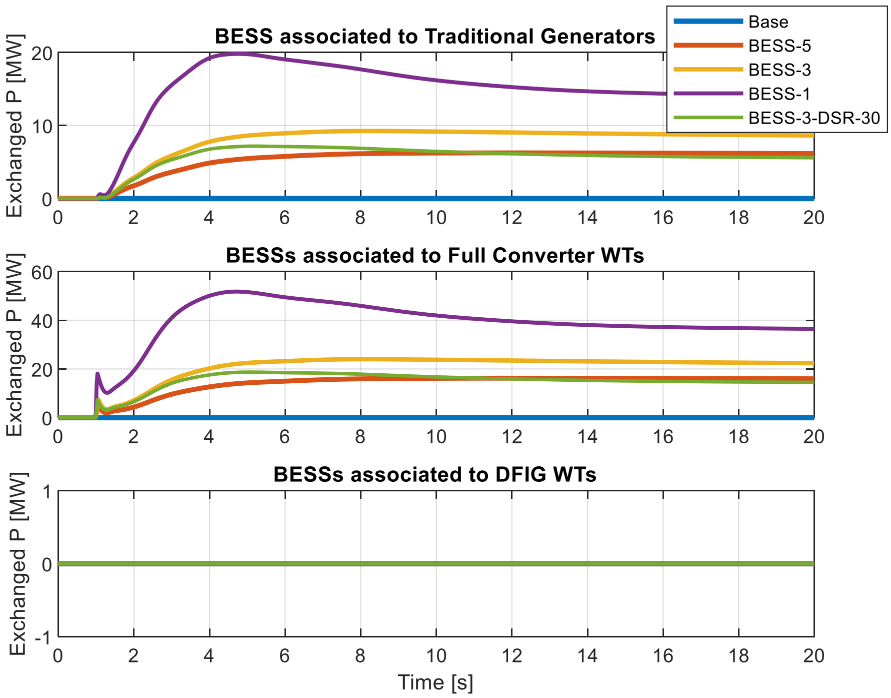

Figure 141. Network: 2050. Dispatching profile: Low Load, Event: outage of all Termini Imerese units and the corresponding BESSs. Power exchanged by BESSs (positive means export, negative means import).

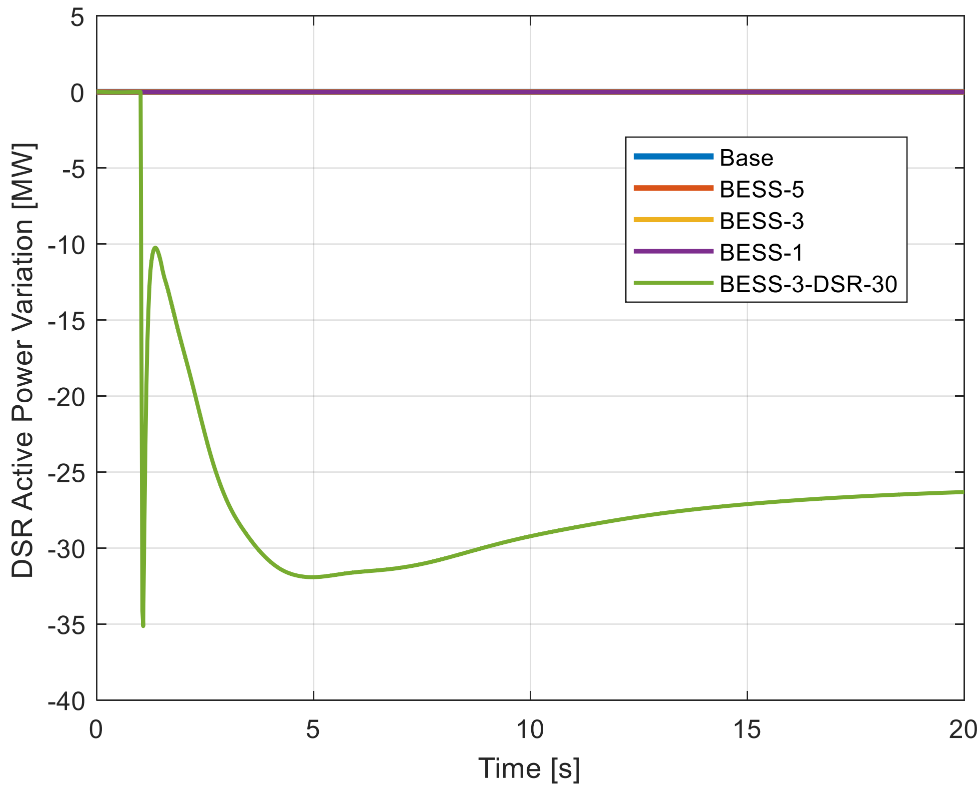

Figure 142. Network: 2050. Dispatching profile: Low Load, Event: outage of all Termini Imerese units and the corresponding BESSs. Total power consumption variation provided by DSR.

4.3.2.6 Lines out of services dispatching profile

In this dispatching profile, the events reported in the following have been simulated:

- **load-step occurring in continental Italy:** emulation of the loss of 500 MW of generated power;
- **outage of one of the three connections with continental Italy**;
- **outage of two of the three connections with continental Italy**;
- **outage of all Termini Imerese units (Snom = 946 MVA) and the corresponding BESSs (Snom = 189 MVA):** total loss of 337 MW of injected power.

The DSR and BESS FCR network configurations listed in Table 16 have been considered:

Network Configuration	K_{BESS}^{tot} [MW]	K_{DSR}^{tot} [MW]	K^{tot} [MW]	% DSR	% Loads Operating 5 % DSR	% Loads Operating 10 % DSR
BESS-5	59	0	59	0 %	0 %	0 %
BESS-3	98	0	98	0 %	0 %	0 %
BESS-1	292	0	292	0 %	0 %	0 %
BESS-1 DSR-30	292	70	362	5 %	92 %	46 %
BESS-1 DSR-50	292	116	408	8 %	153 %	77 %

*Total Load = 1514 MW

Table 16. Network 2050. Dispatching profile: Lines out of services. DSR/BESS FCR network configuration parameters.

4.3.2.6.1 Load-step in continental Italy

The following Figure 143 and Figure 144 report the simulation results obtained with the 500 MW load-step in continental Italy. We can observe that **without the contribution of DSR and BESSs, the limit of 49.9 Hz for normal operating conditions is violated**. A total additive reserve of 408 MW, realized with the configuration BESS-1 DSR-50 (see Table 16), is required to obtain a steady-state value approximately equal to 49.9 Hz, with a minimum of about 49.89 Hz. **In any case, frequency stability is guaranteed also in the base configuration**.

Figure 145 shows the power exchanged through the three connections with continental Italy. Sicily is importing power when simulation starts. Then, when the load-step occurs, import is reduced to support the frequency regulation. We can observe how the contribution to frequency regulation provided from Sicily increases as the BESSs droop coefficient decreases and the percentage of loads operating DSR increases.

Figure 146 shows the active power exchanged by the BESSs associated to in-service traditional generators, FCWT and DFIG plants. Moreover, BESSs are not exchanging power when simulation starts. Since all DFIG plants are out of service, also the corresponding BESSs are all out of service. When the perturbation occurs, in-service BESSs increase their power export to support the frequency regulation. As expected, the provided power variation is higher as lower is the droop coefficient.

Figure 147 reports the variation of the active power absorbed by loads operating DSR. We can observe that, as frequency decreases, the power demand is reduced to support frequency regulation. Clearly, the contribution of loads is higher as higher is the percentage of participating loads.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

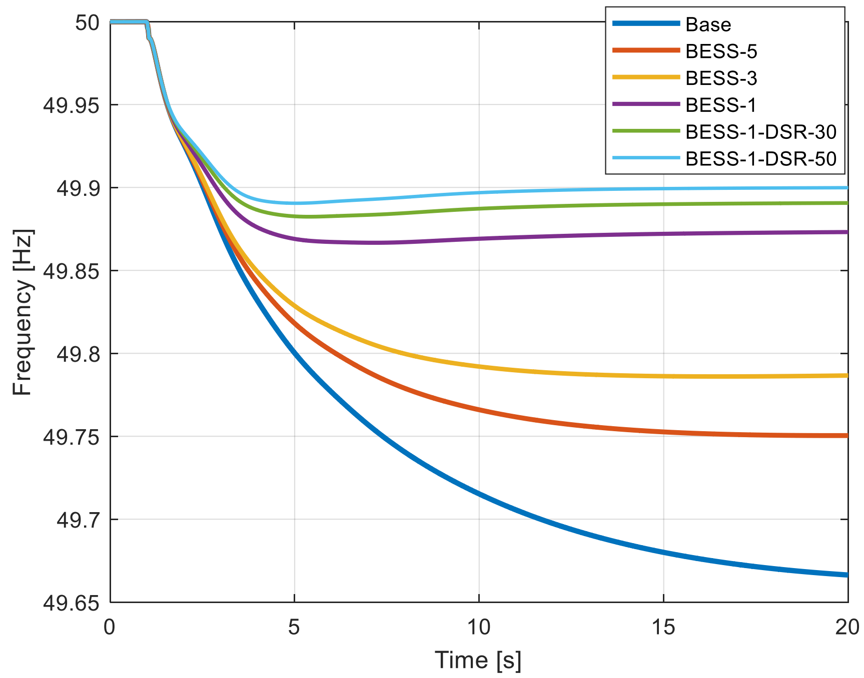

Figure 143. Network: 2050. Dispatching profile: Lines out of service, Event: load-step in continental Italy. Frequency profiles.

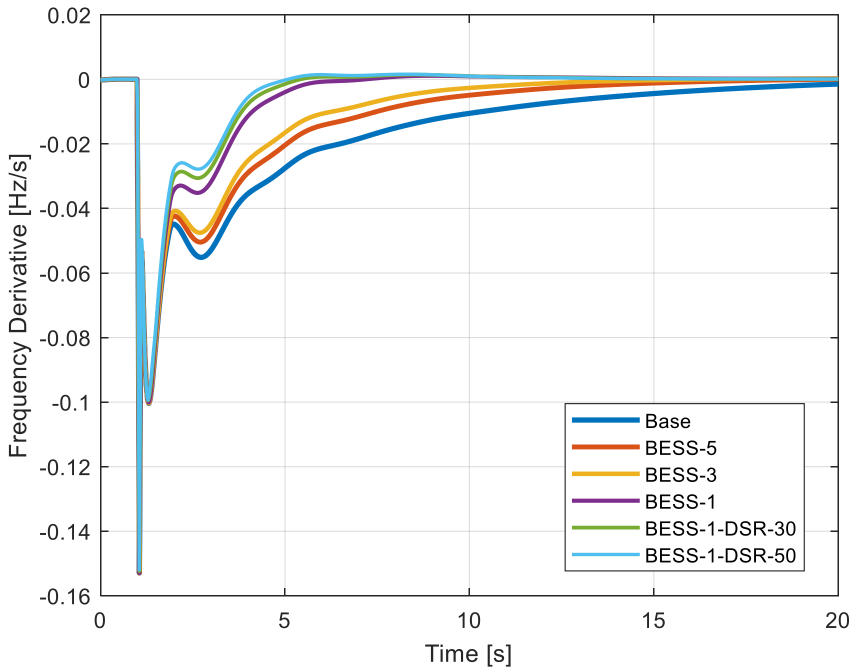

Figure 144. Network: 2050. Dispatching profile: Lines out of service, Event: load-step in continental Italy. Frequency derivative profiles.

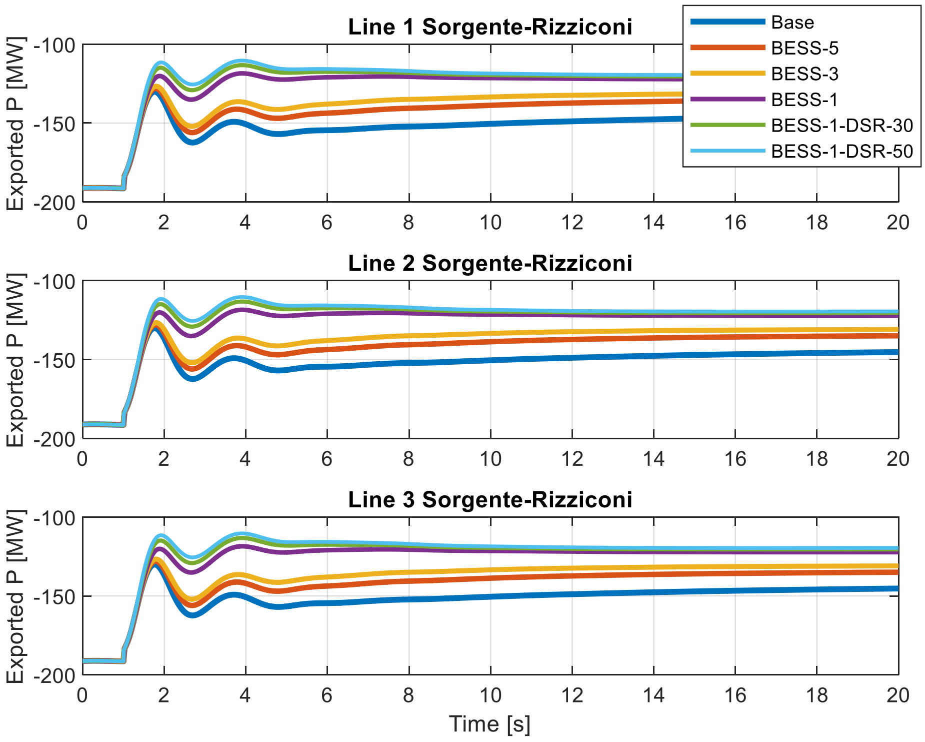

Figure 145. Network: 2050. Dispatching profile: Lines out of service, Event: load-step in continental Italy. Power exported from the Sorgente terminal through the three connections with continental Italy.

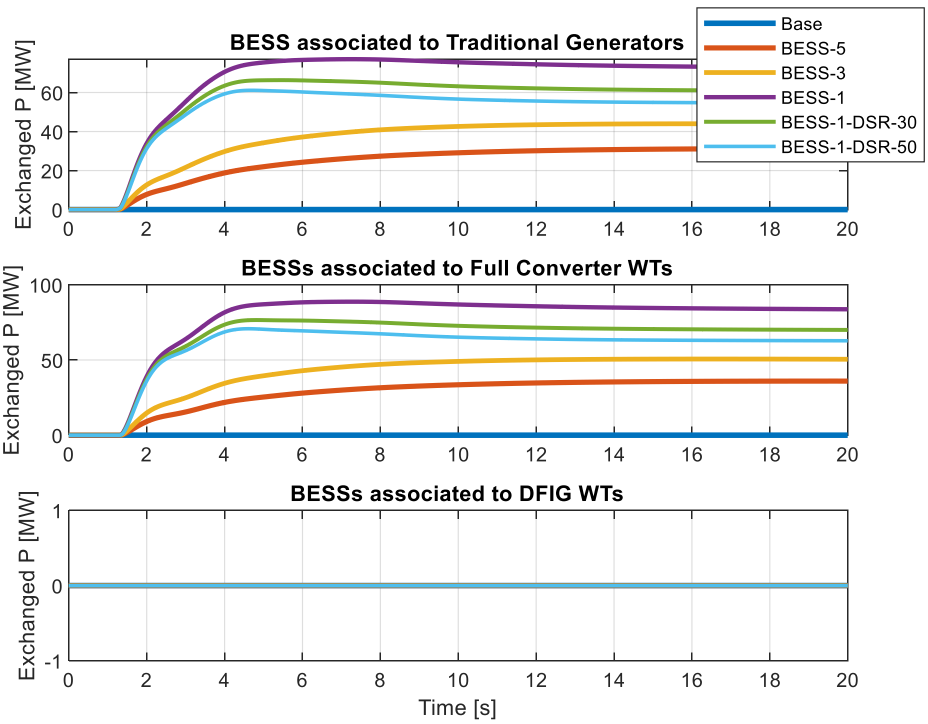

Figure 146. Network: 2050. Dispatching profile: Lines out of service, Event: load-step in continental Italy. Power exchanged by BESSs (positive means export, negative means import).

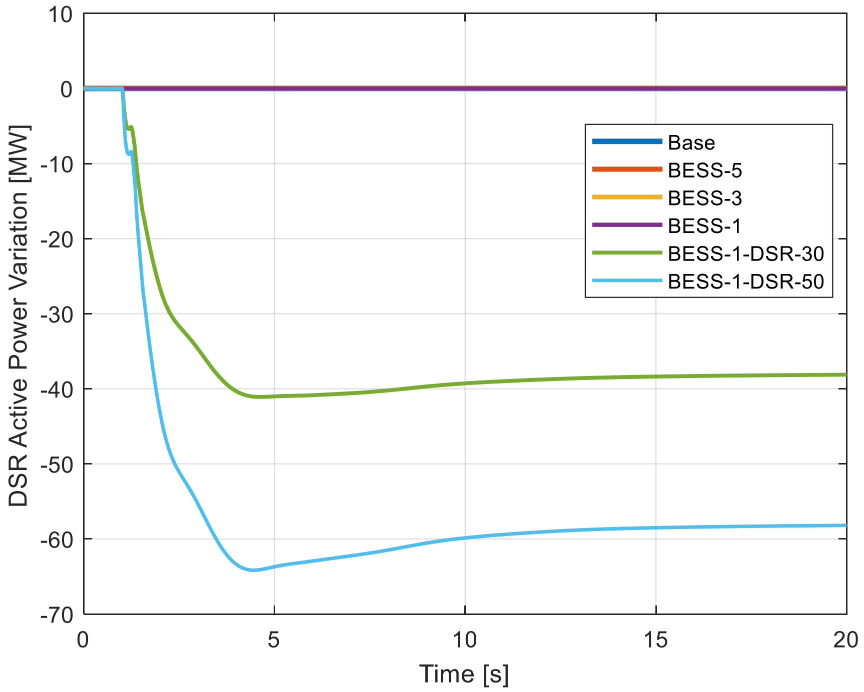

Figure 147. Network: 2050. Dispatching profile: Lines out of service, Event: load-step in continental Italy. Total power consumption variation provided by DSR.

4.3.2.6.2 Outage of one of the three connections with continental Italy

The following Figure 148 and Figure 149 report the simulation results obtained with the loss of one of the three connections with continental Italy. It can be observed that **frequency stability is guaranteed without using BESSs and DSR.**

Figure 150 shows the power exchanged through the three connections with continental Italy. We can observe that the power exported by the lost connection is distributed to the two remaining connections.

We verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

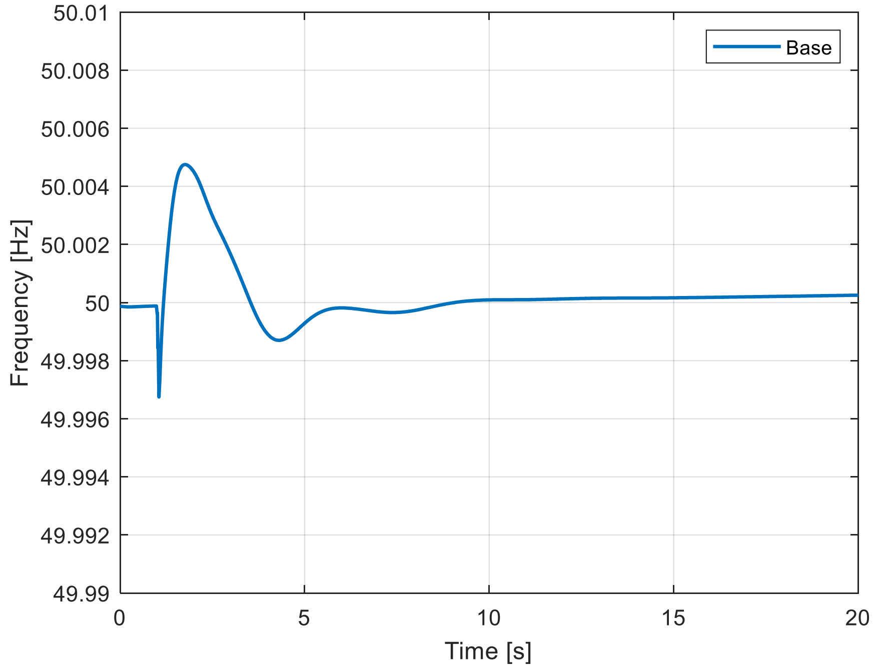

Figure 148. Network: 2050. Dispatching profile: Lines out of service, Event: outage of one of the three connections with continental Italy. Frequency profiles.

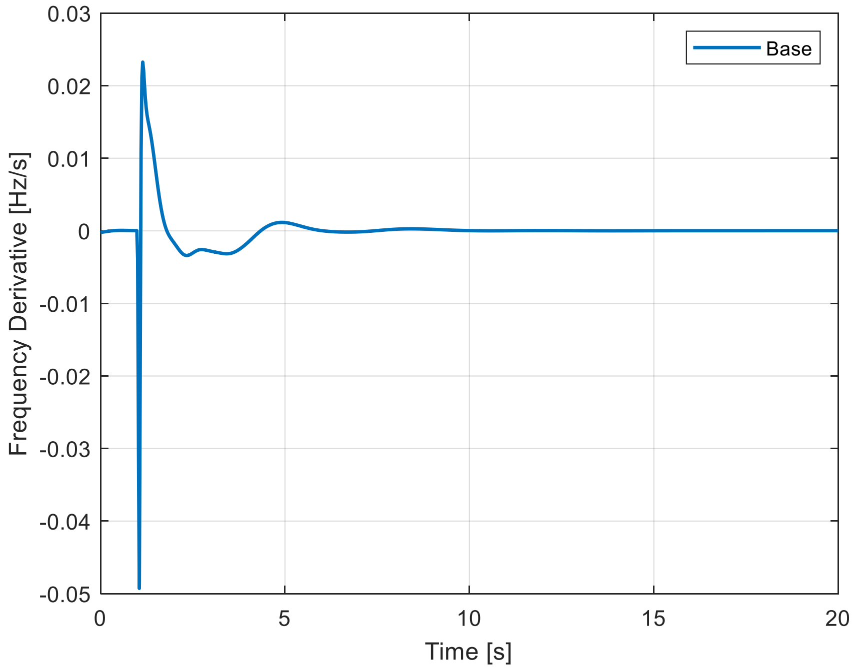

Figure 149. Network: 2050. Dispatching profile: Lines out of service, Event: outage of one of the three connections with continental Italy. Frequency derivative profiles.

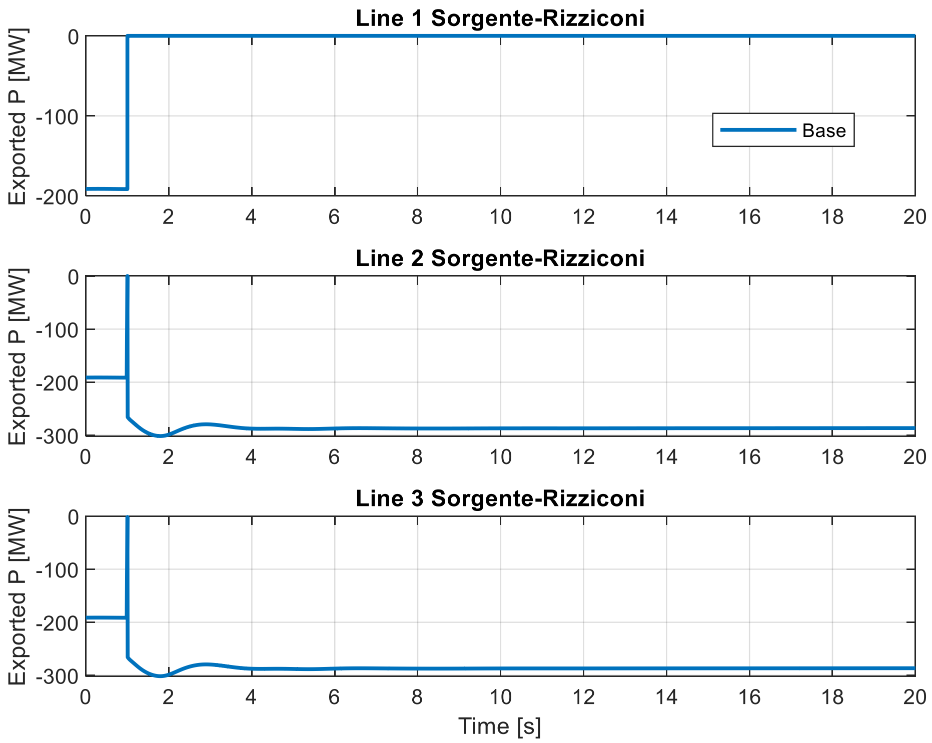

Figure 150. Network: 2050. Dispatching profile: Lines out of service, Event: outage of one of the three connections with continental Italy. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.2.6.3 Outage of two of the three connections with continental Italy

The following Figure 151 and Figure 152 report the simulation results obtained with the loss of two of the three connections with continental Italy. It can be observed that frequency stability is guaranteed without using BESSs and DSR.

Figure 153 shows the power exchanged through the three connections with continental Italy. We can observe that the power imported by the two lost connections is covered by the third connection.

We verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

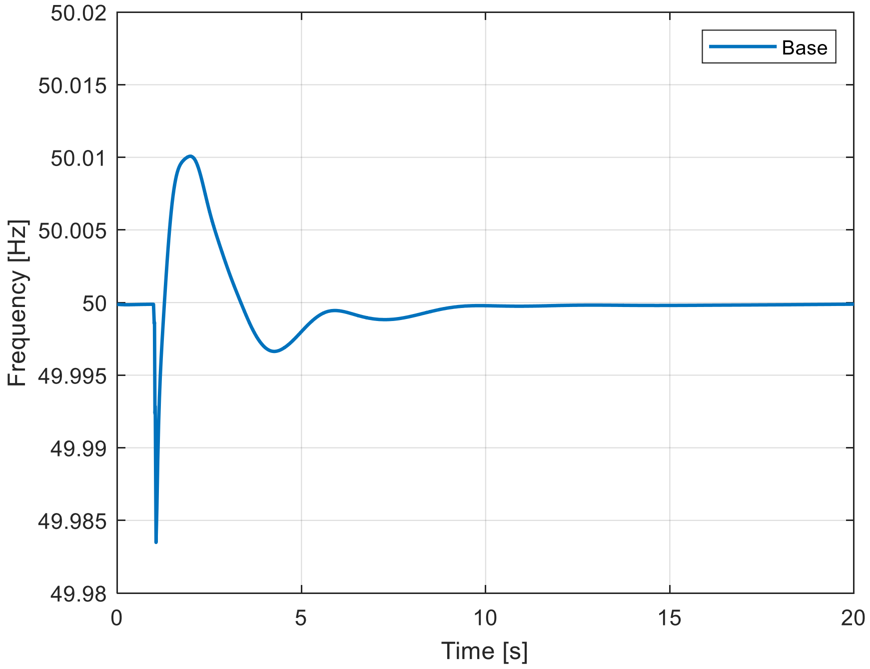

Figure 151. Network: 2050. Dispatching profile: Lines out of service, Event: outage of two of the three connections with continental Italy. Frequency profiles.

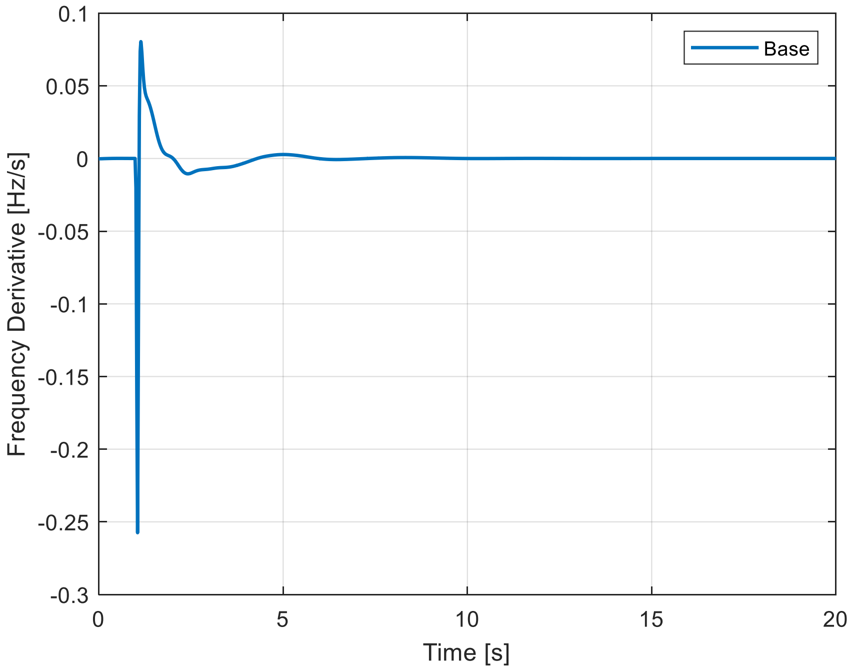

Figure 152. Network: 2050. Dispatching profile: Lines out of service, Event: outage of two of the three connections with continental Italy. Frequency derivative profiles.

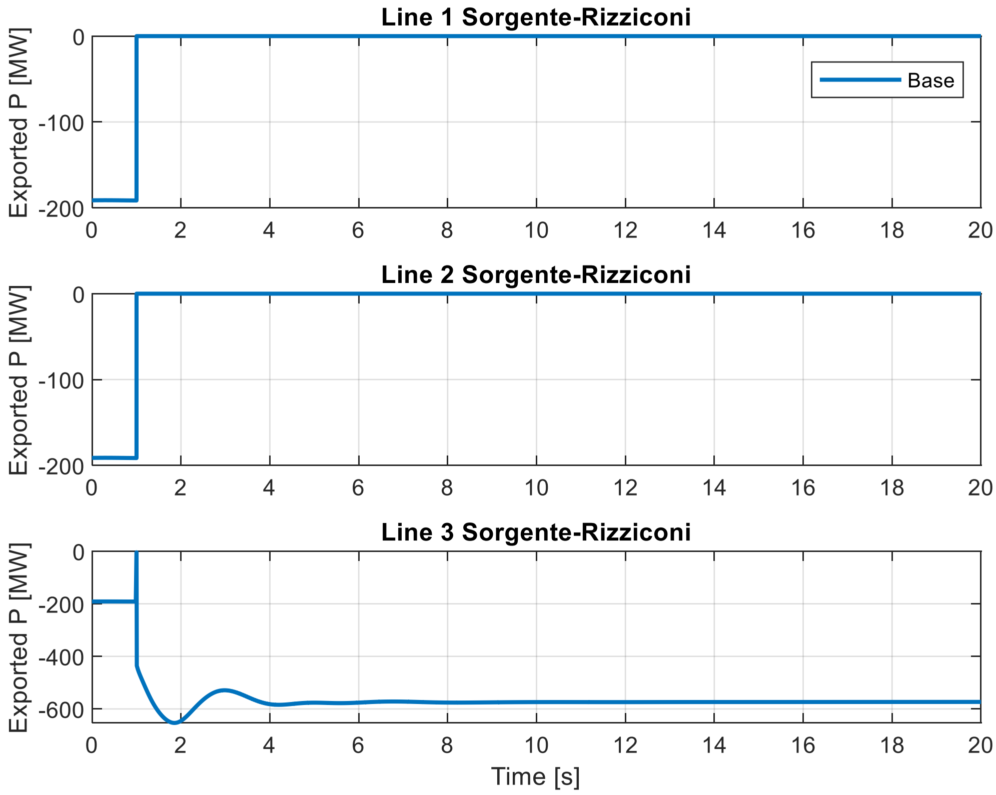

Figure 153. Network: 2050. Dispatching profile: Lines out of service, Event: outage of two of the three connections with continental Italy. Power exported from the Sorgente terminal through the three connections with continental Italy.

4.3.2.6.4 Outage of all Termini Imerese units and the corresponding BESSs

The following Figure 154 and Figure 155 report the simulation results obtained with the outage of all Termini Imerese units and the corresponding BESSs (loss of 337 MW of generated power). We can observe that without the contribution of DSR and BESSs **the limit of 49.9 Hz for normal operating conditions is violated**. In this case, a total additive reserve of 362 MW, realized with the configuration BESS-3 DSR-30 (see Table 16), **is sufficient to keep frequency higher than 49.9 Hz. Notice that also with the configuration BESS-1, frequency is kept higher than 49.9 Hz. In any case, stability is always guaranteed, also with the base configuration.**

Figure 156 shows the power exchanged through the three connections with continental Italy. We can observe that import is increased because of the loss of generation occurring in Sicily. This variation is reduced as higher is the contribution of BESSs and DSR.

Figure 157 shows the active power exchanged by the BESSs associated to in-service traditional generators, FCWT and DFIG plants. Moreover, BESSs are not exchanging power when simulation starts. Since all DFIG plants are out of service, also the corresponding BESSs are all out of service. When the perturbation occurs, in-service BESSs increase their power export to support the frequency regulation. As expected, the provided power variation is higher as lower is the droop coefficient.

Figure 158 reports the variation of the active power absorbed by loads operating DSR. We can observe that, as frequency decreases, the power demand is reduced to support frequency regulation. An initial large decrease of power consumption is registered during the very first instants after the perturbations. This happens because loads provide synthetic inertia.

In all the cases, we verified that currents measured at the two terminals of the each of the three connections between Sicily and the Italian peninsula are lower than the rated value, which is equal to 2 kA.

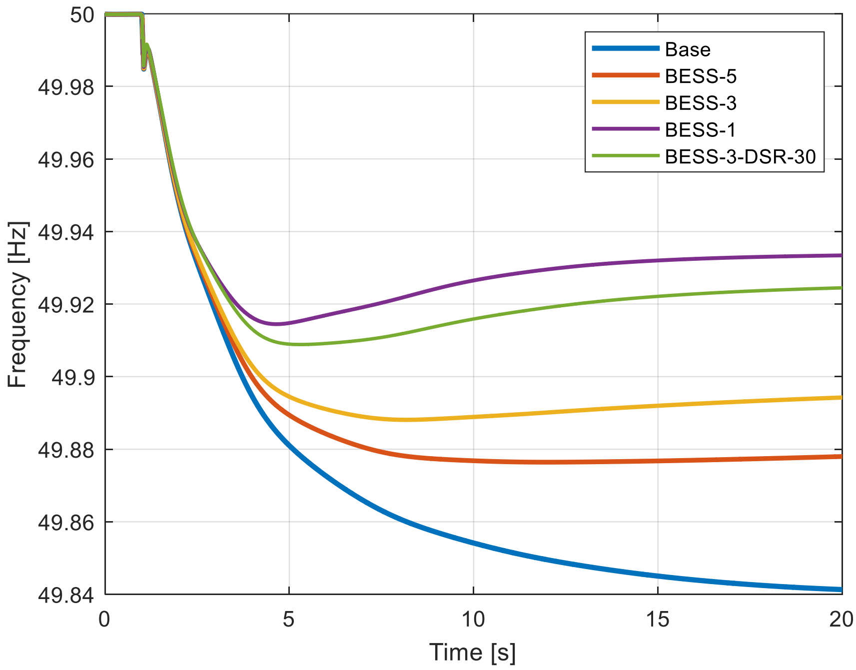

Figure 154. Network: 2050. Dispatching profile: Lines out of service, Event: outage of all Termini Imerese units and the corresponding BESSs. Frequency profiles.

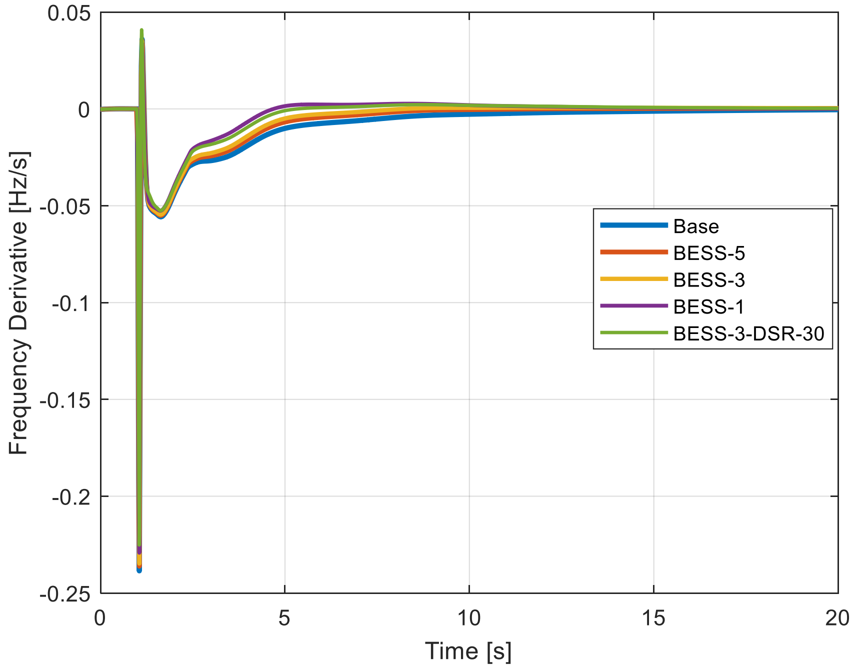

Figure 155. Network: 2050. Dispatching profile: Lines out of service, Event: outage of all Termini Imerese units and the corresponding BESSs. Frequency derivative profiles.

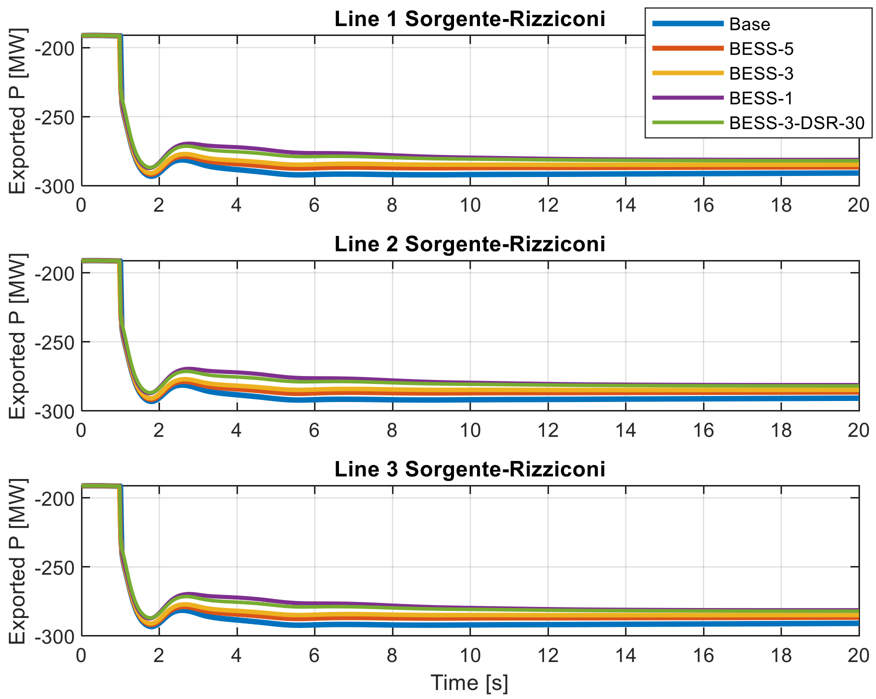

Figure 156. Network: 2050. Dispatching profile: Lines out of service, Event: outage of all Termini Imerese units and the corresponding BESSs. Power exported from the Sorgente terminal through the three connections with continental Italy.

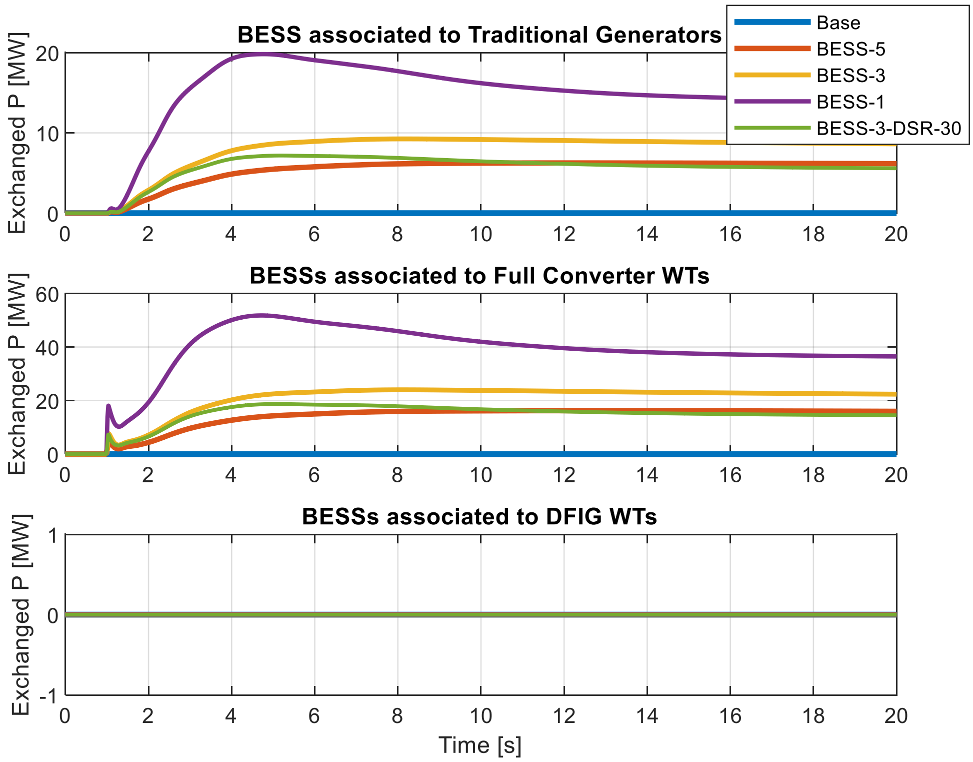

Figure 157. Network: 2050. Dispatching profile: Lines out of service, Event: outage of all Termini Imerese units and the corresponding BESSs. Power exchanged by BESSs (positive means export, negative means import).

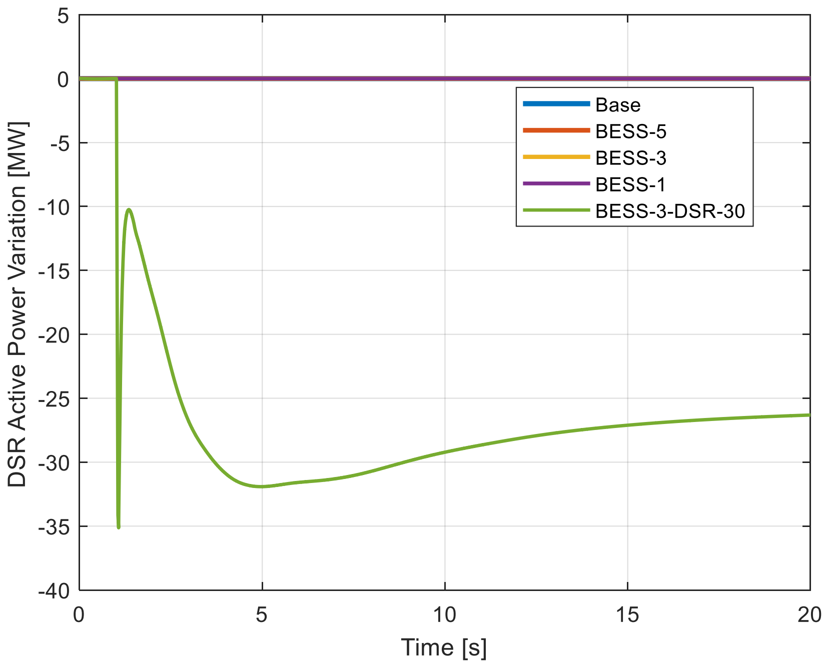

Figure 158. Network: 2050. Dispatching profile: Lines out of service, Event: outage of all Termini Imerese units and the corresponding BESSs. Total power consumption variation provided by DSR.

4.3.2.7 2050 Conclusions

The frequency stability of the power system of Sicily, forecasted for the year 2050, has been analysed. Six different dispatching profiles have been studied:

1. **High Export**, characterized by quite high wind production, no photovoltaic, low load demand, and a consequent high-power export from Sicily to continental Italy;
2. **High Import**, characterized by almost no renewable production, medium/high demand, and a consequent high level of power import from continental Italy to Sicily;
3. **High Load**, characterized high load demand, high wind and photovoltaic production;
4. **Island**, with high photovoltaic and wind production;
5. **Low Load**, characterized by low load and almost zero wind production;
6. **Lines out of service**, which is the *Low Load* profile with two lines out of service.

For each dispatching profile, a set of events has been simulated to study the frequency dynamical response. 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* one). Moreover, a 500 MW load-step occurring in continental Italy and the outage of different groups of traditional generating units have been simulated (load-step in continental Italy was not simulated in the *Island* profile).

First of all, for each event, the base network configuration, with no power reserve (FCR) provided by flexible loads (DSR) and/or by BESSs, has been tested, checking if:

i. frequency stability is guaranteed,
ii. normal operating conditions are guaranteed (defined by the Italian grid code [19] as the range 49.9 Hz – 50.1 Hz when Sicily is connected with continental Italy and as the range 49.5 Hz – 50.5 Hz in islanded mode).

Whenever one of these two conditions were not satisfied, different network configurations, where BESSs and\or DSR provide FCR, have been tested looking for the best configuration. The amount of FCR has been progressively increased, giving priority to the use of BESSs, by varying the equivalent droop coefficient from 5 to 1 % and, when necessary, adding DSR, progressively increasing the percentage p of the provided FCR with respect to the flexible loads operating point (see Section 4.3.1 for details).

Table 17 summarizes the obtained results. For each dispatching profile and each event, the table reports if the two mentioned conditions have been satisfied with the base network configuration. In the cases where one of the conditions is not satisfied, Table 17 reports the FCR provided with the best BESSs-DSR configuration and if, in this case, the two conditions have been successfully satisfied.

Event	Base network configuration		Best BESSs – DSR network configuration			
	Stability?	Normal operating conditions?	Configuration	FCR	Stability?	Normal operating conditions?
High Export						
Load-step in c. Italy (500 MW)	YES	NO	BESS-1 DSR-25	655 MW	YES	YES
Outage of one link w. c. Italy	YES	YES	Not required	-	-	-
Outage of two links w. c. Italy	YES	YES	Not required	-	-	-
Generation outage (220 MW)	YES	YES	Not required	-	-	-
High Import						
Load-step in c. Italy (500 MW)	YES	NO	BESS-5 DSR.15	203 MW	YES	YES
Outage of one link w. c. Italy	YES	YES	Not required	-	-	-
Outage of two links w. c. Italy	NO	NO	BESS-1	522 MW	YES	YES
Generation outage (321 MW)	YES	YES	Not required	-	-	-
Generation outage (569 MW)	YES	NO	BESS-3 DSR-25	338 MW	YES	YES
Generation outage (817 MW)	YES	NO	BESS-1 DSR-35	751 MW	YES	NO
High Load						
Load-step in c. Italy (500 MW)	YES	YES	Not required	-	-	-
Outage of one link w. c. Italy	YES	YES	Not required	-	-	-
Outage of two links w. c. Italy	YES	YES	Not required	-	-	-
Generation outage (337 MW)	YES	YES	Not required	-	-	-
Island						
Generation outage (337 MW)	YES	NO	BESS-3	174 MW	YES	YES
Low Load						
Load-step in c. Italy (500 MW)	YES	NO	BESS-1 DSR-30	362 MW	YES	YES
Outage of one link w. c. Italy	YES	YES	Not required	-	-	-
Outage of two links w. c. Italy	YES	YES	Not required	-	-	-
Generation outage (337 MW)	YES	NO	BESS-1	292 MW	YES	YES

Event	Base network configuration		Best BESSs – DSR network configuration			
	Stability?	Normal operating conditions?	Configuration	FCR	Stability?	Normal operating conditions?
Lines out of service						
Load-step in c. Italy (500 MW)	YES	NO	BESS-1 DSR-50	406 MW	YES	NO
Outage of one link w. c. Italy	YES	YES	Not required	-	-	-
Outage of two links w. c. Italy	YES	YES	Not required	-	-	-
Generation outage (337 MW)	YES	NO	BESS-3 DSR-30	362 MW	YES	YES

Table 17 – Network 2050. Simulation results summary.

As we can observe in Table 17, frequency stability is guaranteed in all the dispatching profiles and for all events, except for the outage of two connections with continental Italy in the *High Import* one. In this case, the outage of two connections causes to the loss of the third remaining connection because of the high level of imported power (1188 MW). As a consequence, Sicily is completely disconnected from continental Italy, losing a large amount of power import and the rotating and power reserves coming from the rest of the Italian power system. It is worth remarking that such a situation is very unrealistic and would never occur in the real power system, being addressed differently in the operational planning phase. 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 in facts not present in the real Italian network) leading to its trip and causes the islanding of Sicily. However, we studied this case as an extreme situation to assess the potential of flexibility resources available.

To obtain frequency stability in such a critical hourly profile, the contribution of BESSs and/or DSR results to be mandatory. Using only BESSs with a 5 % droop, stability has been obtained only thanks to a load shedding of 547 MW. Augmenting the contribution of BESSs with a 3 % droop, load shedding has been reduced to 290 MW. Finally, increasing again the contribution of BESSs, with a 1 % droop, corresponding to an FCR of 522 MW, stability and normal operating conditions has been guaranteed without activating load shedding. It is worth remarking that this profile is particularly critical and determined by the disconnection of three lines, which is an extremely unlikely event.

Always observing results in Table 17, we notice that in some cases, with the base network configuration, normal operating conditions are violated, even if stability is guaranteed. This never happens in the *High Load* profile, where the number of generating units (conventional plants and wind turbines), all providing FCR, is sufficient to keep the normal operating conditions without requiring the contribution of BESSs and\or DSR. In the other dispatching profiles with Sicily connected to the Italian peninsula, the 500 MW load-step occurring in continental Italy causes the violation of the normal operating conditions with the base configuration. **In these cases, the contribution to frequency regulation of BESSs and/or DSR is always sufficient to keep frequency in the range 49.9 Hz – 50.1 Hz.**

Further cases where the contribution of BESSs and/or DSR is required to keep normal operating conditions are the outages of large traditional generating units in the *High Import*, *Island*, *Low Load* and *Lines out of service* profiles. **In most cases, a suitable mix of BESSs and DSR FCR is sufficient to guarantee normal operating conditions. In only two cases this has resulted not possible.**

The first one is the outage of all Termini Imerese generating units in the *High Import* profiles, that causes the loss of 817 MW generated power. Actually, with the configuration BESS-1 DSR-35, corresponding to an FCR of 751 MW, the violation is of only 0.02 Hz for about 4 seconds, and the frequency steady-state value is equal to 49.9 Hz. It is clear that augmenting again the DSR participation percentage from 35 % will allow not violating the threshold. A higher value has been not tested since, in this dispatching profile, p = 35 % is equivalent to an FCR equal to the 7 % of the total load in Sicily, and to the case of 71% of loads operating a 10 % droop and to the 142 % of loads operating a 5 % droop (see Table 13).

The second one is the load-step in continental Italy in the *Lines out of service* profile, where an FCR of 406 MW provided with the mix BESS-1 DSR-50 was not sufficient to keep frequency higher than 49.9 Hz. However, also in this case, the threshold violation is temporary (about 7 seconds) and limited to about 0.02 Hz. The contribution of DSR has been limited to $p = 50$ % since it corresponds to the 8 % of the total load in Sicily, and to the case of 77 % of loads operating a 10 % droop and to the 153 % of loads operating a 5 % droop (see Table 16).

The general conclusions of this study are that, based on the forecast for 2050:

- except for the unlikely case of disconnection from continental Italy, large perturbation stability can be guaranteed with no difficulties without the need of a contribution from BESSs and/or DSR;
- in low load dispatching profiles, with a low level of traditional and wind generation, to guarantee normal operating conditions a support from BESSs and/or DRS is required;
- no voltage problems or congestion issues have appeared during simulations.

5 Small perturbation angle stability analysis

This chapter summarizes the results carried out by ENSiEL (in particular, University of Bologna) for the OSMOSE project, WP1, subtask 1.4.3, in regard to small signal stability analysis on the same scenario and operating conditions already considered in the previous chapter. In the following, a description of the procedure adopted is presented, the PSS block scheme of synchronous generators is shown, and finally the results of the small perturbation angle stability for the 2030 and 2050 dispatching profiles, concerning the Sicilian grid, are presented and discussed.

5.1 Procedure

To perform the small signal stability analysis, the classical modal/eigenvalue analysis tool, available in DIgSILENT, has been used. The modal analysis tool determines the state matrix $\boldsymbol{A}$ using numerical algorithms and calculates its eigenvalues using a standard QR method. The idea is to write the matrix as a product of an orthogonal matrix and an upper triangular matrix, multiply the factors in the reverse order, and iterate.

A dynamic system described by state matrix $\boldsymbol{A}$ is said to be stable to small angle perturbations if all eigenvalues $\lambda = \sigma + j\omega$ have negative real part. Damping refers to pairs of complex eigenvalues $\lambda = \sigma \pm j\omega$, which introduce oscillatory modes with frequency equal to $f = \frac{\omega}{2\pi}$, and it is a measure of the rate of decay of the amplitude of the oscillations. To quantify this, the damping ratio is introduced:

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{6}$$

which corresponds to the opposite of the real part of the eigenvalue divided by its module. The damping ratio, if the mode is stable, is a number included between 0 and 1. Given this definition, an unstable mode has a negative damping ratio and a positive and purely real eigenvalue has a damping ratio of -1 or, in percentage, of -100 %. In the practice of electric power systems, a system is said to be acceptable, and oscillations properly damped, if for every mode $\zeta \geq 0.05$ (i.e., if the damping ratio is greater than 5 %). In some cases, to be more conservative, a value of 10 % is used, but usually 5 % is the considered threshold of stability. In this report, eigenvalues with a damping ratio above 10 % are filtered out and those below 5 % are considered unacceptable (because poorly damped).

An important role in power system small perturbation angle stability analysis is played by the right eigenvectors of state matrix $\boldsymbol{A}$. If the eigenvectors are normalized, then the i^{th} element of right eigenvector *k*, that is $w_k(i)$, determines the share of modal variable $z_k(t)$ in the activity of state variable $x_i(t)$. This is usually referred to as observability or mode shape. The mode shape represents an inherent feature of a linear dynamic system and does not depend on where and how a disturbance is applied. Regarding electromechanical modes (i.e., modes involving swings of rotors generators), the generator speed mode shape is the key factor for determining the influence of individual oscillatory modes on swings of the rotors of individual generators.

Other important coefficients are the participation factors, obtained multiplying element by element left and right eigenvectors related to the same mode. Participation factors are a good measure of correlation between modes and state variables; they are typically used to determine the siting of stability enhancing devices (typically, PSSs). Generally, a stabilizer is preferably installed where the modal variables associated with a given eigenvalue are both well observable and controllable (i.e., the magnitude of the participation factor is large). Electromechanical modes can be identified as those modes in which rotor angle deviation and rotor speed deviation have a large participation factor. These types of modes will be the primary focus of this report. 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 by the magnitude of the participation vector and the angle of the observability. Plotting the oscillation vectors allows identifying the state variables mainly involved in that mode and, by looking at the angle differences, understand how the oscillations are manifested in the state variables, e.g., if in phase or counter-phase.

In formulas, the oscillation vector of state variable x_i with respect to mode *k* is:

$$ov_{ki} = |pf_{ki}|\angle w_k(i) \tag{7}$$

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 observability vector *k* (i.e., the right eigenvector associated to mode *k*). This feature will be used to identify the properties specific to each relevant oscillation mode, in particular electromechanical modes, and the behaviour of the involved generators.

As an example, in Figure 159 the oscillation vector of the inter-area mode of the well-known “two-areas four-generators” system by Kundur is shown [5]. The interpretation of this oscillation vector is that, if a disturbance excites this mode, the rotor speeds of generators 3 and 4 will swing, coherently to each other, in counterphase with respect to those of generators 1 and 2, which in turn will swing coherently. Since the two pairs of generators belong to two different areas, this allows inferring that the considered mode is an inter-area mode, characteristic which is also confirmed by its low frequency. Furthermore, by looking at the magnitude of the oscillation vectors, that is the participation factor, we can understand that the oscillations of generators 3 and 4 will be significantly more severe than those of generators 1 and 2.

Electromechanical modes can be generally classified in three categories depending on the location of the generators involved. In order of increasing frequency, inter-area modes involve generator belonging to distinctly different areas of the grid (e.g., Sicily and the peninsula), inter-plant or local modes are modes involving units of the same area but different plant, intra-plant modes are modes involving units of the same plant. Throughout the report, modes presenting the same dynamic phenomenon, hence with a very similar oscillation vector, will be referred to using the same denomination. As an example, the inter-area mode involving generators in Sicily and the generator slack in the peninsula, identified by its oscillation vector, will be referred to, for the relevant dispatching profiles, as M1.

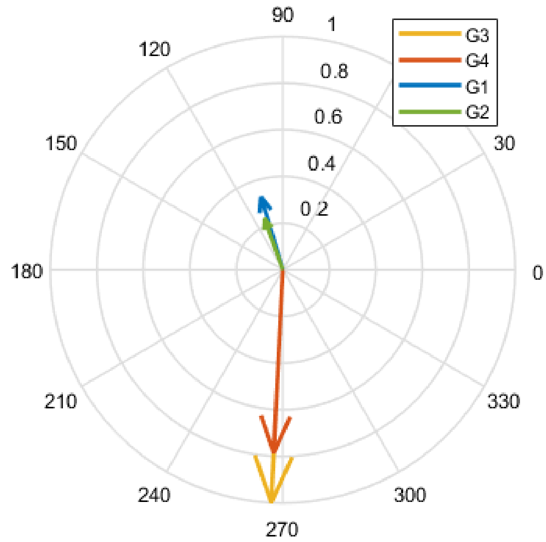

Figure 159. Oscillation vector of the well-known inter-area mode of "two-areas four-generators" system found in Kundur [5].

5.2 Power system stabilizer

Of the synchronous generators installed in the 2030 and 2050 Sicilian network, generators with power of 70 MVA or greater are equipped with a composite model with Governor (GOV), Automatic Voltage Regulator (AVR) and Power System Stabilizer (PSS). The PSS provides a further input signal to the exciter system to provide additional damping to the electromechanical oscillations of the power system through exciter control. The type of power system stabilizers adopted is assumed to be the PSS2B, its block scheme is shown in Figure 160. PSS2B takes both rotational speed deviation and electrical power deviation as its inputs. The main composition of the model includes:

- Washout Block: the washout block consists of one or several washout filters, and the washout block provides filtering of dc components present in the input signal whereas components of higher angular frequency are passed. Without the presence of the washout filter in the PSS, the terminal voltage would be affected by steady increases in the rotor angular frequency;
- Synthetization Block: the synthetization block generates the stabilizing signal based on one or multiple input signals;
- Gain Block: the gain block determines the amount of damping provided by the PSS. We will refer to it, throughout the report, as K_{PSS};
- Phase Compensation Block: the phase compensation block consists of three first order lead-lag filters where the time constants of the lead-lag filters can be set independently. It provides phase lead compensation;
- Output Limiter Block: it keeps the output from the PSS within certain limits. This block is needed to avoid large fluctuations in the terminal voltage during the transient state.

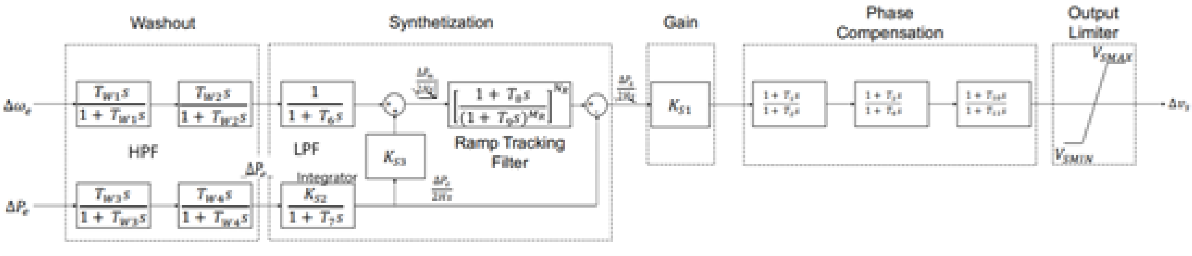

Figure 160. PSS model (PSS2B) utilized in the network.

5.3 2030 Network

First, the different dispatching profiles described in 3.1.2 for the year 2030 are analysed, then the contribution to small signal stability provided by RES and synthetic inertia is investigated as well as the optimal tuning of the PSS. Analysis is focused on oscillatory modes with damping ratio below 10 %, with those with a damping ratio below 5 % being the critical ones. If not specified, all the other modes are stable and properly damped. The contribution from Synthetic Inertia (SI) scheme implemented on the Full Converter Wind Turbine (FCWT) is presented and its effect on the low damping modes is studied. Since we will focus on oscillatory modes, specifically electromechanical modes, we list in Table 18 the 23 synchronous generators present in the Sicilian grid, their location, the rated power and the inertia constant. As it can be seen from Figure 161, most of the units and also the largest ones are concentrated in the petrochemical complex of Augusta-Priolo located on the east coast of the Island. Similarly, in Figure 162, the location of all the FCWTs present in the network is shown.

First of all, the following cases will be considered:

- for the FCWT units, no Synthetic Inertia is provided, i.e., SI gain of $K_{IRF} = 0$ is adopted;
- for the PSS of synchronous generators, the gain base case value of $K_{PSS} = 3$ is adopted.

#	Synchronous Generators	Location	Rating (MVA)	H (s)
1	CNTP	Contrasto	24	3.75
2	DITP	Dittaino	22.8	3.75
3	EGNP1	Priolo Gargallo	102	3.75
4	EGNP2	Priolo Gargallo	102	3.75
5	EGNP3	Priolo Gargallo	93.2	6
6	EGNP4	Priolo Gargallo	93.2	6
7	EGNP5	Priolo Gargallo	93.2	6
8	EGNP6	Priolo Gargallo	93.2	6
9	EGSP1	Città Giardino	30	3.75
10	EGSP2	Città Giardino	30	3.75
11	EGSP3	Città Giardino	30	3.75
12	ESSP2	Augusta	58.1	3.75
13	ESSP1	Augusta	18.2	3.75
14	ISBP1	Priolo Gargallo	144	6
15	ISBP2	Priolo Gargallo	200	6
16	PATP	Paternò	9	3.75
17	PRGP2	Priolo Gargallo	288	3.75
18	PRGP1	Priolo Gargallo	370	7.5
19	TEMP	Milazzo	185	3.75
20	TIMP3	Termini Imerese	288	7.5
21	TIMP2	Termini Imerese	288	7.5
22	TIMP1	Termini Imerese	370	3.75
23	TROP	Troina	14	3.75

Table 18. List of synchronous generators and synchronous compensators (19 and 20) in the Sicilian grid.

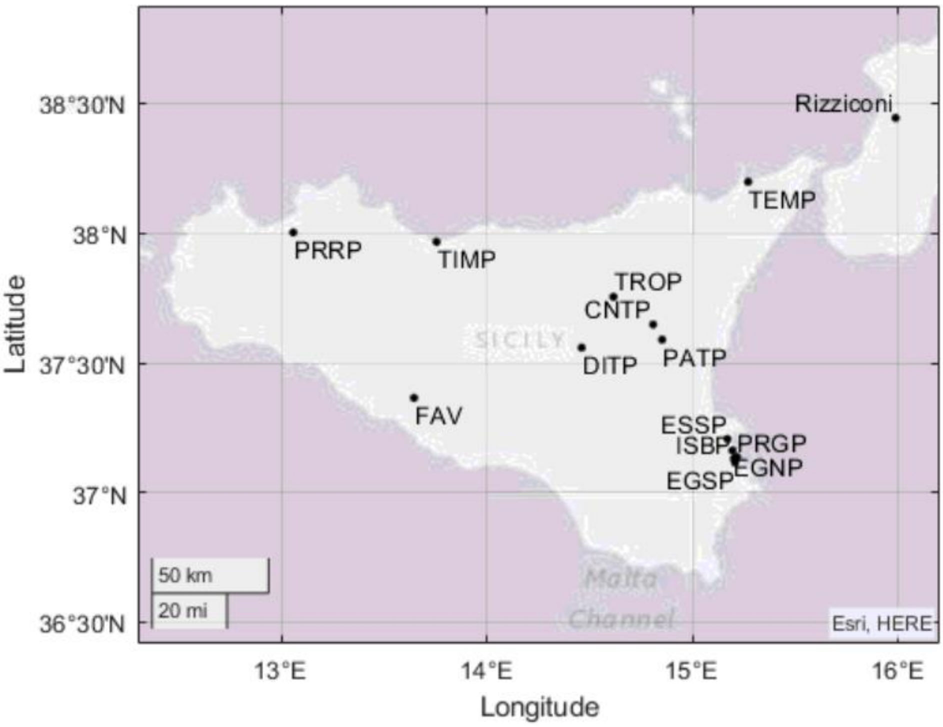

Figure 161. Locations of the synchronous generators in the 2030 network. The slack generator is located on the peninsula in the substation in Rizziconi.

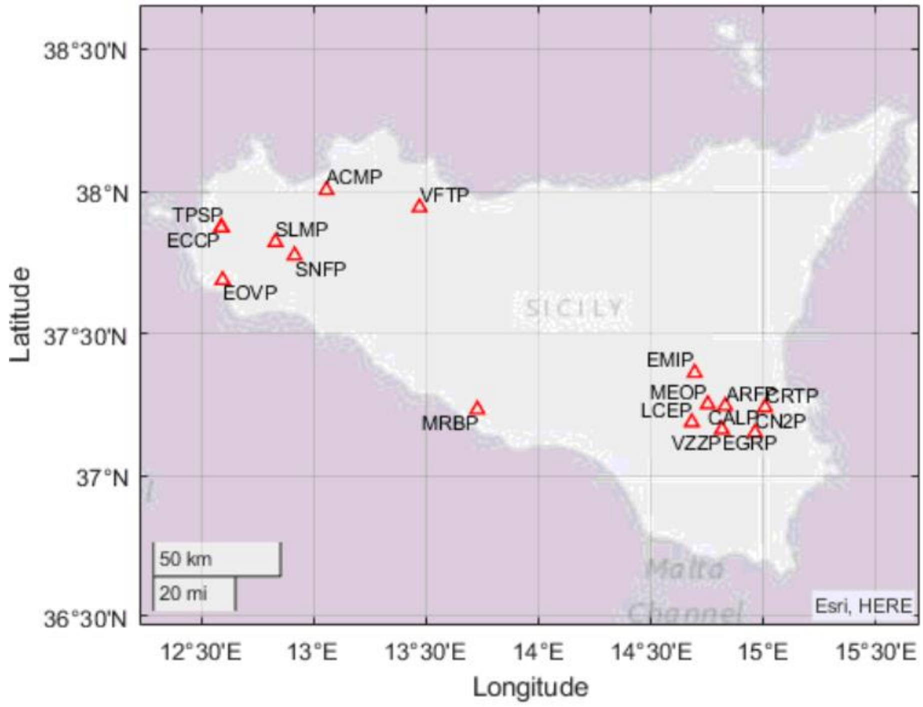

Figure 162. Locations of the Full Converter Wind Turbines in the 2030 network.

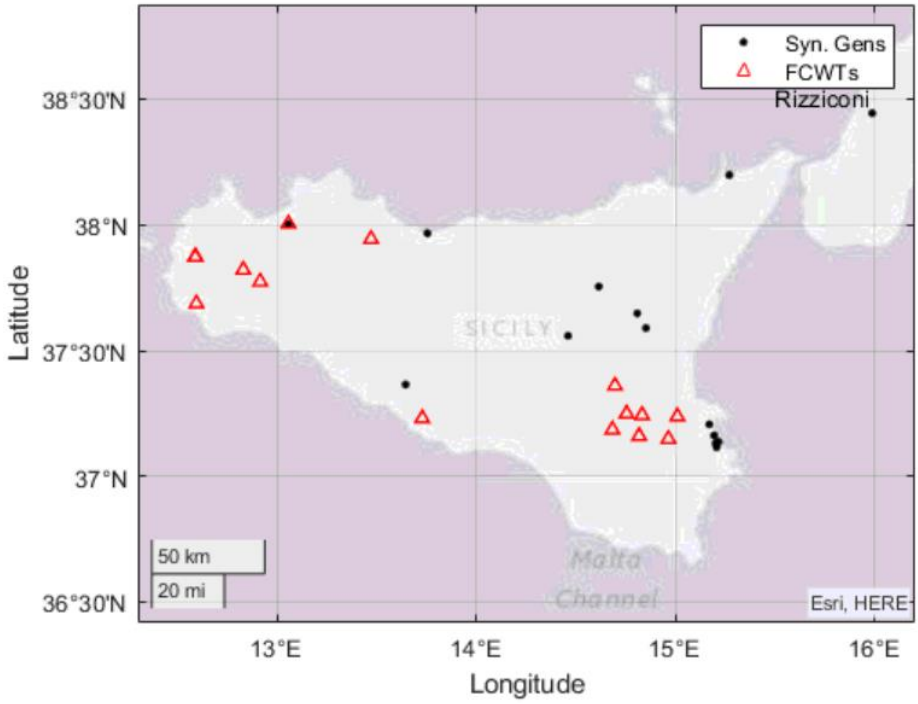

Figure 163. Locations of the synchronous generators and FCWTs substations in the 2030 network.

5.3.1 Base case

5.3.1.1 High Export dispatching profile

For the *High Export* profile, the modal analysis revealed five electromechanical modes with damping ratio below 10 % as shown in Table 19. Mode M1, that represents an inter-area mode, is the only mode with an unacceptable value of damping ratio below 5 % (i.e., 1 %).

Mode	Eigenvalues	Frequency, $f\ (Hz)$	Damping, ζ (%)	Involved Plants
M1	-0.05 ± 4.57j	0.73	1.00	TIMP, PRGP, SLACK
M2	-0.61 ± 8.21j	1.30	7.51	EGSP, PRGP
M3	-0.45 ± 5.58j	0.89	8.13	EGNP, PRGP, ISBP
M4	-0.88 ± 10.02j	1.58	8.84	EGSP
M5	-0.89 ± 9.95j	1.58	8.92	EGSP

Table 19. Electromechanical modes with damping ratio below 10% for the 2030 High Export dispatching profile.

By looking at the oscillation vectors of these modes, it is possible to identify their characteristics and the generators involved:

- M1: In Figure 164 the oscillation vector of mode M1 is shown. The generators mainly affected by this oscillatory mode are the generators of the thermoelectric plant in Termini Imerese, named TIMP1 and TIMP2. It can also be noted that the mode is an inter-area mode (as the frequency suggests) in which the slack generator in Rizziconi oscillates against TIMP1, TIMP2 and the generator in Priolo Gargallo, named PRGP1. However, the participation factors of PRGP1 and of the slack are significantly lower. As we will show in the following, this mode can be properly damped both by tuning the gain of the PSS in TIMP and by providing inertial response through the FCWT;
- M2: In Figure 165 the oscillation vector of mode M2 is shown. This is a local mode in which the generators EGSP1, EGSP2 and EGSP3 oscillate against the generators PRGP1 and PRGP2 which do however have a very low participation factor;
- M3: In Figure 166, the oscillation vector of mode M3 is shown. This local mode is characterized by generators EGNP1 and EGNP2 oscillating against generators ISBP1 and PRGP1;
- M4: In Figure 167 the oscillation vector of mode M4 is reported. This is an intra-plant mode in which EGSP3 oscillates against EGSP1 and EGSP2;
- M5: In Figure 168 the oscillation vector of mode M5 is shown. This is another intra-plant mode of the same plant in which EGSP1 oscillates against EGSP2 and EGSP3.

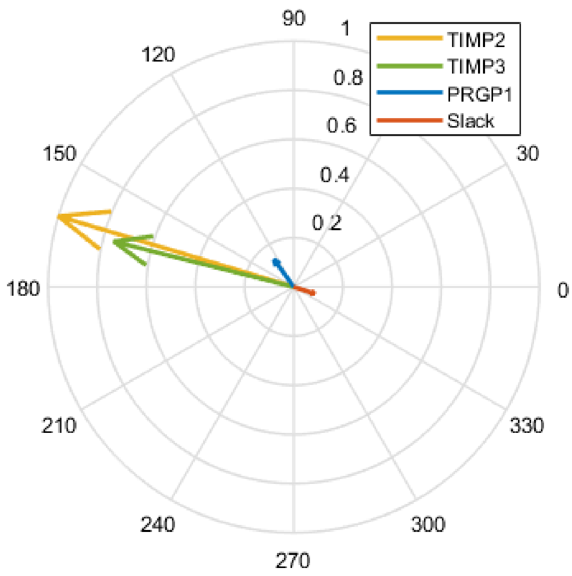

Figure 164. Oscillation vector of the inter-area mode M1.

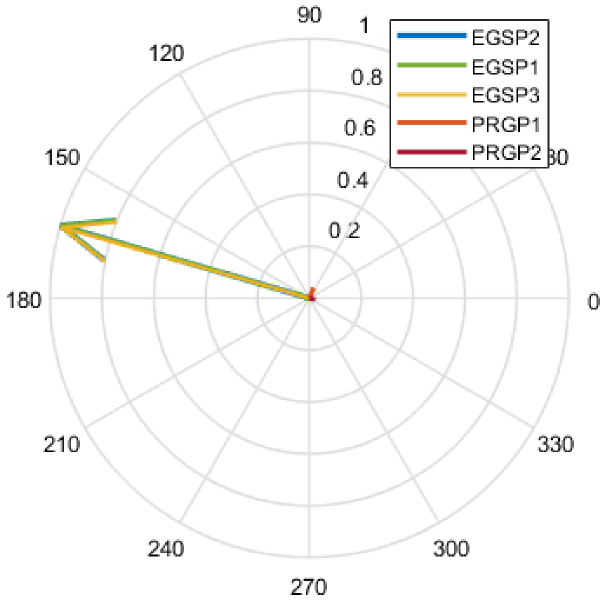

Figure 165. Oscillation vector of mode M2.

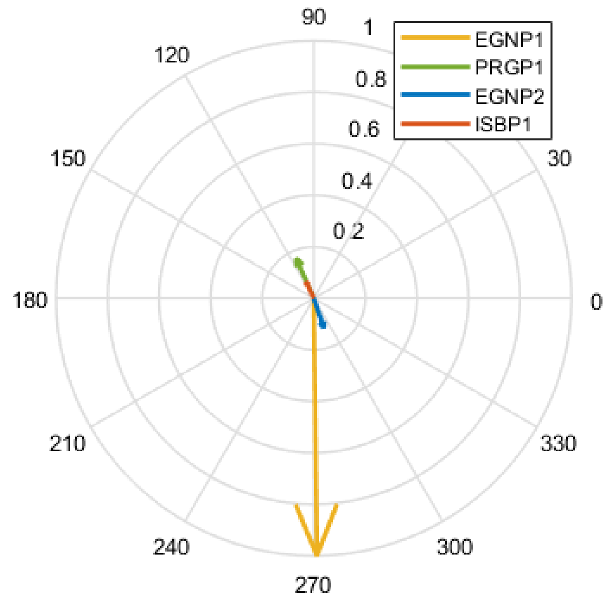

Figure 166. Oscillation vector of mode M3.

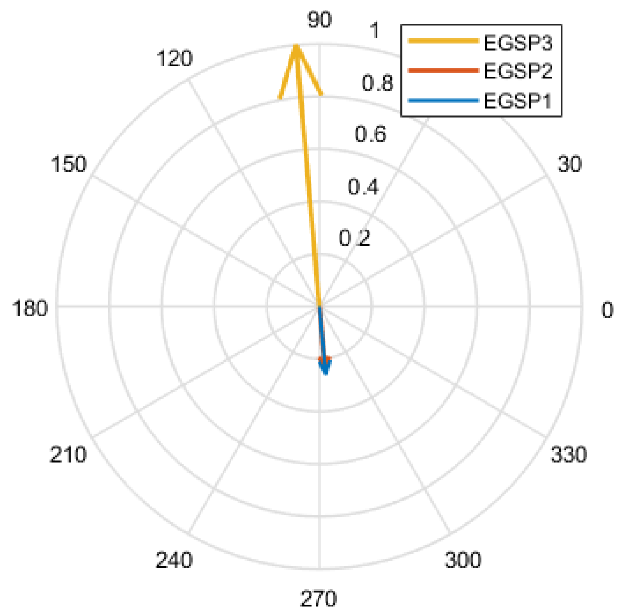

Figure 167. Oscillation vector of mode M4.

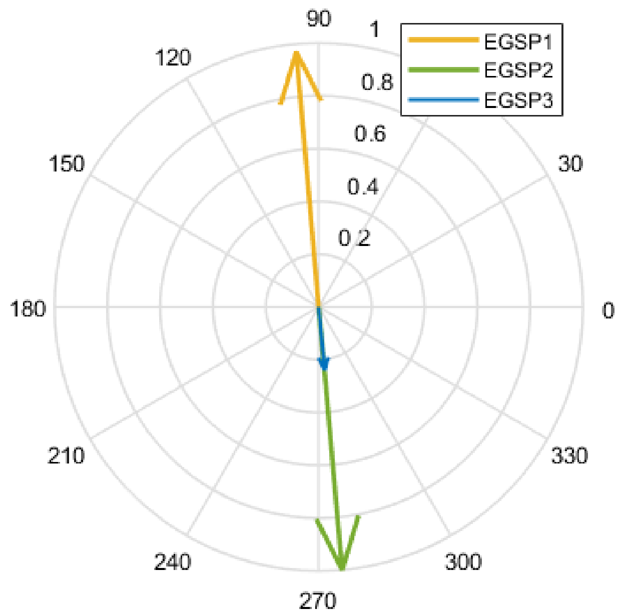

Figure 168. Oscillation vector of mode M5.

5.3.1.2 High Import dispatching profile

For the *High Import* profile, the modal analysis revealed just two electromechanical modes with a damping ratio below 10 %, both properly damped and shown in Table 20. All the other modes are stable. The modes, M1 and M3, are the same already described in the previous profile. However, there is a considerable improvement in the damping ratio of M1 and a slight decrease in frequency. The damping ratio of M1 is in this case above 5 % and the mode is hence well damped. Similarly, the damping ratio of M3 is slightly increased here, compared to the *High Export* profile and the frequency stays the same.

Mode	Eigenvalues	Frequency, $f\ (Hz)$	Damping, ζ (%)	Involved Plants
M1	-0.3 ± 4.22j	0.67	7.20	TIMPP, PRGP, SLACK
M3	-0.5 ± 5.56j	0.89	9.00	EGNP, PRGP, ISBP

Table 20. Modes with a damping ratio below 10% for the 2030 High Import dispatching profile.

5.3.1.3 High Load dispatching profile

In the *High Load* dispatching profile, all oscillatory modes have a damping ratio above 10 %; hence, it does not present any stability concern.

5.3.1.4 Low Load / Low Gas dispatching profile

In the *Low Load / Low Gas* profile, the modal analysis revealed one electromechanical mode with a damping ratio slightly below 10 % as shown in Table 21:

Mode	Eigenvalues	Frequency, $f\ (Hz)$	Damping, ζ (%)	Involved Plants
M6	-1.03 ± 10.8j	1.72	9.50	TROP, EGNP

Table 21. Modes with a damping ratio below 10% for the 2030 Low Load / Low Gas dispatching profile.

This is an electromechanical mode that did not appear in the previous hourly profiles analysed, hence it will be named sequentially (i.e., M6) and its dynamic behaviour is examined by means of the oscillation vector:

- M6: In Figure 169, the oscillation vector of mode M6 is shown. This mode shows the unit in Troina (TROP) oscillating against the one in Milazzo (TEMP). Generator TROP, however, is not equipped with a PSS and has a rated power more than 10 times smaller than generator TEMP, which it is practically not affected by the oscillatory mode, hence justifying the big difference in participation factor magnitudes.

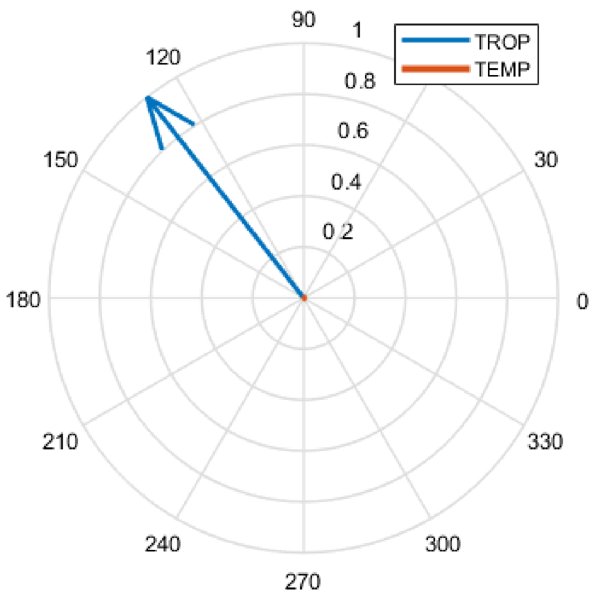

Figure 169. Oscillation vector of mode M6.

5.3.1.5 Island dispatching profile

In the *Island* profile, all oscillatory modes have damping ratio greater than 10 %; hence, it does not present any stability concern.

5.3.1.6 Line out of Service dispatching profile

In the *Line out of service* profile, all oscillatory modes have damping ratio greater than 10 %; hence, it does not present any stability concern regarding small perturbations.

5.3.2 RES contribution and PSS tuning

In this section, the contribution of renewable energy sources to the small perturbation stability is evaluated, that is, the synthetic inertia provided by the Full Converter Wind Turbines (FCWT) which is the only RES present in the 2030 Sicilian grid. Eventually, the gain of the relevant generators PSS is tuned to increase the overall stability of the grid and in particular the damping ratio of the critical mode M1; lastly, the effect of the two combined actions is presented.

5.3.2.1 Full Converter Wind Turbine Synthetic Inertia

In this subsection, the contribution to the small signal stability of the DC-link-based Inertia Response (IR) provided by the full converter wind turbine units is investigated. For the base case profiles, the setting of the frequency controller gain K_{IRF} was set to 0, i.e., no synthetic inertia was provided. The subscript IRF stands for Inertia Response FCWT. The value of the K_{IRF} gain is incremented in steps of 10 until reaching 50 i.e., K_{IRF} = [0, 10, 20, 30, 40, 50], and the modal analysis is repeated for each value and all the dispatching profiles. In the following tables, the first row is the starting value, and the check mark symbol indicates that the mode has a damping ratio above 10 % and hence it is more than properly damped. The results are hereby discussed:

- For the *High Load*, *Island* and *Line out of service* profiles, the presence or absence of IR provided by the FCWT does not introduce any oscillation with damping lower than 10%;
- For the *High Export* dispatching profile, the results are shown in Table 22. Increasing the value of K_{IFR} increases the damping ratio of M1 to a maximum value of 5.6% for K_{IRF}=40. In this way, the low damped inter-area mode becomes properly stabilized. Modes M2 and M3 experience a minor decrease in damping ratio with increasing values of K_{IRF}. Modes M4 and M5 are not affected. A sixth electromechanical mode with damping factor below 10 % appears in the *High Export* one. This mode experiences minor reduction in damping ratio with increasing K_{IRF} and will be named A1;
- For the *High Import* profile, the results are presented in Table 22Table 22. Change in frequency and damping ratio of the electromechanical modes for increasing values of the gain KIRF related to the SI provided by FCWT in the High Export dispatching profile.

- The damping ratio of M1, starting from a value of 7.2 %, increases above the 10% threshold for K_{IRF} values above 20. Regarding M3, increasing values of K_{IRF} lead to a minor reduction of its damping ratio, from 9.0 % to 8.7 %. K_{IRF} values of 20 and above, allow a mode that in the base case analysis had a damping ratio above 10 % to drop below the threshold. The damping ratio of this mode, named A2, experiences a slight reduction with increasing values of K_{IRF};
- For the *Low Load / Low Gas* dispatching profile, the results are presented in Table 23.M6, the only electromechanical mode here present, is not affected at all by increasing values of K_{IRF}.

K_{IRF}	M1		M2		M3		M4		M5		A1	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
0	0.73	1.0	1.3	7.5	0.89	8.1	1.58	8.84	1.58	8.92	✓	✓
10	0.73	3.0	1.3	7.4	0.89	7.9	1.58	8.84	1.58	8.92	1.66	9.9
20	0.73	4.6	1.3	7.3	0.89	7.7	1.58	8.84	1.58	8.92	1.66	9.8
30	0.74	5.4	1.3	7.3	0.89	7.6	1.58	8.84	1.58	8.92	1.66	9.8
40	0.75	5.6	1.3	7.2	0.89	7.6	1.58	8.84	1.58	8.92	1.66	9.8
50	0.75	5.6	1.3	7.2	0.89	7.5	1.58	8.84	1.58	8.92	1.66	9.7

Table 22. Change in frequency and damping ratio of the electromechanical modes for increasing values of the gain K_{IRF} related to the SI provided by FCWT in the High Export dispatching profile.

K_{IRF}	M1		M3		A2	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
0	0.67	7.2	0.89	9.0	✓	✓
10	0.67	9.4	0.89	8.95	✓	✓
20	✓	✓	0.89	8.86	1.28	9.95
30	✓	✓	0.89	8.78	1.28	9.91
40	✓	✓	0.89	8.72	1.28	9.89
50	✓	✓	0.89	8.68	1.28	9.87

Table 23. Change in frequency and damping ratio of the electromechanical modes for increasing values of the gain K_{IRF} related to the SI provided by FCWT in the High Import dispatching profile.

K_{IRF}	M6	
	f (Hz)	ζ (%)
0	1.72	9.5
10	1.72	9.5
20	1.72	9.5
30	1.72	9.5
40	1.72	9.5
50	1.72	9.5

Table 24. Change in frequency and damping ratio of the electromechanical modes for increasing values of the gain KIRF related to the SI provided by FCWT in the Low Load / Low Gas dispatching profile.

5.3.2.2 PSS gain tuning

In this subsection, the effect of the PSS gain on the electromechanical modes with damping below 10 % is investigated. At first, the FCWTs are assumed to provide no SI i.e., K_{IRF}=0, so to study the effects separately. In the next subsection, their combined effect is examined. The locations of the generators equipped with PSS are indicated in Figure 170 and correspond to those with a power rating higher than 70 MVA.

For each dispatching profile, the generators equipped with PSS, and with a high participation factor in the electromechanical modes with a damping factor below 10 %, have been identified and the gain of their PSS has been tuned, while the PSS gain of all the other generators has been kept constant. In particular, the main goal is to properly damp the oscillation of the critical inter-area mode M1, in which the TIMP generators oscillate against the slack. The value of the PSS gain, starting from a value of 0, has been gradually increased. Different values of K_{PSS} = [0, 0.5, 1, 2, 3] p.u. have been adopted, the modal analysis is repeated for each dispatching profile and the effect on the electromechanical modes has been examined.

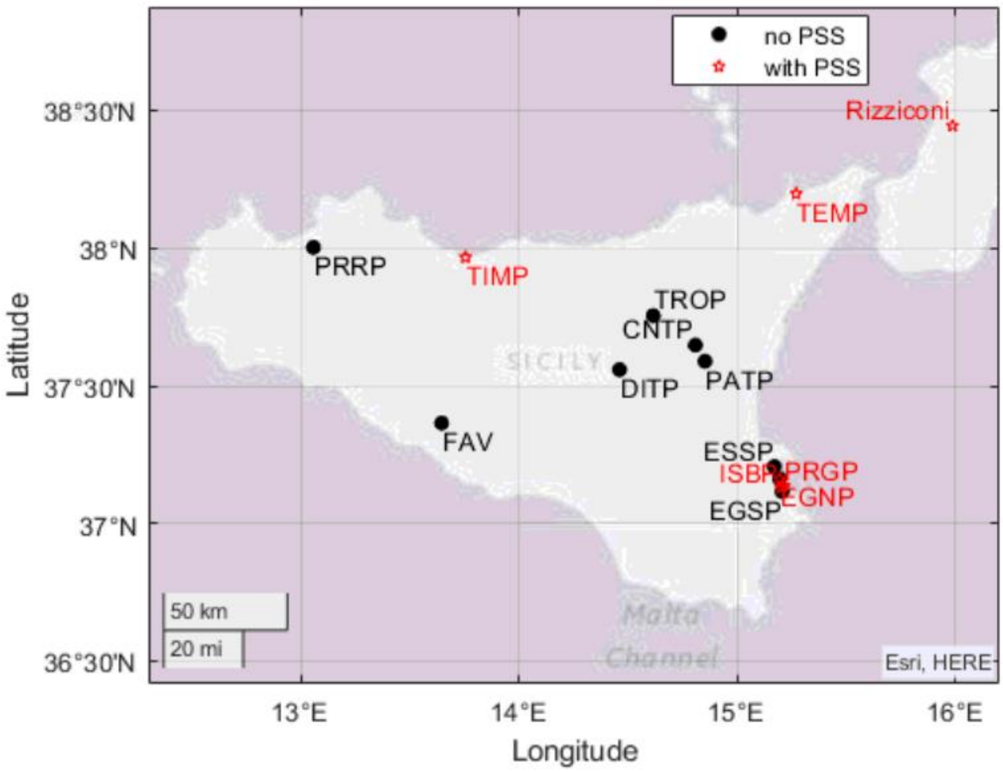

Figure 170. Locations of all synchronous generators, in red those equipped with PSS.

For the *High Export* profile, the results are shown in Table 25. Since the generators of the TIMP and EGNP plants have, respectively, a high participation factor in the modes M1 and M3 and are both equipped with PSS, these are the PSS that have been tuned. The results show that, for modes M1 and M3, an increasing value of the PSS gain is not necessarily beneficial and a value ranging between 0.5 and 1 p.u. is best solution.

The damping ratio of the poorly damped inter-area mode M1, starting from a value of 8.0 %, becomes not properly stabilized for PSS gain values greater than 1, and reaches its lowest damping for the default PSS gain value, that is K_{PSS}=3 p.u. Regarding the damping ratio of M3, starting from a value of 8.7 % it reaches its maximum value of 9.0 % for a PSS gain value equal to 0.5 and decreases for higher values of the gain. Modes M2, M4 and M5 involve generators not equipped with PSS; their damping ratio is unaffected and remains above 5 %. Without PSS for generators TIMP and EGNP, that is K_{PSS}=0, two modes (A3 and A5) present a damping ratio below 10 % and mode A4 below 5 %. Increasing the value of the gain to a value ranging between 0.5 and 1 p.u. allows for a proper stabilization of these modes. In conclusion, for the *High Export* dispatching profile, the optimal value of K_{PSS} that allows all modes to be properly damped ranges between 0.5 and 1.

K_{PSS} of TIMP and EGNP (p.u.)	M1		M2		M3		M4		M5		A3		A4		A5	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
0	0.78	8.0	1.3	7.5	1.0	8.7	1.58	8.84	1.58	8.92	1.65	9.8	1.5	2.5	1.58	9.4
0.5	0.78	7.0	1.3	7.5	1.0	9.0	1.58	8.84	1.58	8.92	1.65	9.9	1.5	6.5	✓	✓
1	0.75	3.4	1.3	7.5	0.93	8.7	1.58	8.84	1.58	8.92	✓	✓	✓	✓	✓	✓
2	0.75	3.4	1.3	7.5	0.93	8.7	1.58	8.84	1.58	8.92	✓	✓	✓	✓	✓	✓
3	0.73	1.0	1.3	7.5	0.89	8.1	1.58	8.84	1.58	8.92	✓	✓	✓	✓	✓	✓

Table 25. Variation in frequency and damping ratio of the electromechanical modes for increasing values of the gain K_{PSS} related to the plants TIMP and EGNP in the High Export dispatching profile. The first row is the starting value and check marks indicate modes with damping ratio above 10%.

For the *High Import* dispatching profile, the results are reported in Table 26 and they are similar to the *High Export* dispatching profile. Values of K_{PSS} above 1 p.u. are not beneficial for modes M1 and M3, and values below 0.5 p.u. destabilize mode A4 that becomes less and less damped. For this reason, also in the *High Import* profile, a value of K_{PSS} ranging between 0.5 (necessary to damp inter-area mode M1 in the *High Export* profile) and 1 is the most suitable.

K_{PSS} of TIMP and EGNP (p.u.)	M1		M3		A4	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
0	✓	✓	✓	✓	1.5	2.1
0.5	✓	✓	✓	✓	1.5	6.0
1	✓	✓	✓	✓	✓	✓
2	✓	✓	0.92	9.9	✓	✓
3	0.67	7.2	0.89	9.0	✓	✓

Table 26. Change in frequency and damping ratio of the electromechanical modes for increasing values of the gain K_{PSS} related to the plants TIMP and EGNP in the High Import dispatching profile.

Summarizing, it has been found that the optimal value of K_{PSS} for generators TIMP and EGNP, that provides the best solution in each hourly profile ranges between 0.5 and 1 p.u. This allows to effectively damp the inter-area mode M1, increasing its damping ratio above 5 % without compromising the damping of other modes.

5.3.2.3 Combined Influence of Frequency Support Schemes of FCWT and PSS tuning

In this subsection, the combined influence on the small signal stability of tuning the PSS and providing FCWT based SI is investigated. As it has shown in the previous two subsections, both measures are independently capable to provide a significant stability enhancement. The base case analysed in section 5.3.1 is compared to the optimal case in which the relevant PSS are tuned and FCWT provide IR. The two optimal values previously identified for the PSS and IR gain are, respectively, K_{PSS} = 1 p.u for generators TIMP and EGNP, and K_{IRF} = 30 p.u. for the FCWT. Considering these values, the results are shown in Table 27 for the *High Export* dispatching profile and inTable 28 for *High Import* one, the combined action of PSS tuning and SI provided by the FCWT provides excellent results in terms of mode damping. In fact, the previously poorly damped inter-area mode M1 is effectively damped to a value greater than 10 %, the damping ratio of Mode M3 is increased, modes M2, M4, M5 are little affected and the damping ratio of mode A1 is very close to the 10 % threshold.

Case	M1		M2		M3		M4		M5		A1	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
Base	0.73	1.0	1.3	7.5	0.89	8.1	1.58	8.84	1.58	8.92	✓	✓
Optimal	✓	✓	1.3	7.3	0.98	9.0	1.58	8.84	1.58	8.91	1.66	9.7

Table 27. Frequency and damping ratio of the electromechanical modes, in the High Export dispatching profile, for the most suitable values of the relevant PSS generators gain, K_{PSS}, and the SI gain, K_{IRF}, of FCWT.

Case	M1		M3		A2	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
Base	0.67	7.22	0.89	9.0	✓	✓
Optimal	✓	✓	✓	✓	1.28	9.9

Table 28. Frequency and damping ratio of the electromechanical modes, in the High Import dispatching profile, for the most suitable values of the relevant PSS generators gain, K_{PSS}, and the SI gain, K_{IRF}, of FCWT.

5.3.3 2030 Conclusions

Regarding the stability of the system to small perturbations, the simulations performed on the developed model, **concerning 2030, allow concluding that the system does not present major stability issues**. The *High Export* dispatching profile is the only one presenting in the base conditions a not properly damped oscillatory mode. That mode is inter-area, involving the equivalent generator in Calabria and the power plant near Termini Imerese, and its **stability can be improved thanks to the synthetic inertia contribution provided by wind farms, and by tuning of the relevant PSSs**. The *Low Load* and the *High Import* dispatching profiles present, respectively, one and two electromechanical modes with damping ratio above 5 % and below 10 %, thus well damped. All the other profiles, *High Load*, *Island* and *Lines out of service* do not show any mode with a damping ratio below the conservative threshold of 10 %.

The contribution of synthetic inertia provided by Full Converter Wind Turbines and PSS tuning has been assessed both separately and together. A sensitivity analysis of the eigenvalues with respect to the synthetic inertia gain and PSS gain has been performed. The results show how the stability of poorly damped modes improves introducing the contribution of synthetic inertia and tuning the PSS gain of the most relevant plants. Specifically, it has been found that the optimal value for the **gain of the synthetic inertia is 30 and its contribution can stabilize the inter-area mode**. Regarding the PSS, the generators mainly affected by the poorly damped electromechanical modes have been identified by use of the oscillation vectors and their PSS properly tuned. It has been found that a major role is played by the plant in Termini Imerese, and the results show that **a value of the PSS gain ranging from 0.5 to 1 stabilizes the poorly damped inter-area mode without introducing any drawbacks**. Combining the contribution from SI and PSS tuning the stability of the system is greatly improved and **all modes have a damping ratio well above 5 %.**

In conclusion, the analysis has shown that the local modes within Sicily do not present stability concerns. This is also strengthened by the fact that the *Island* dispatching profile, in which Sicily is disconnected from the continent, does not present modes with critically low damping ratios. The inter-area mode, modelling the interactions between Sicily and the continent, is the only concern to small perturbation stability and has been properly stabilized by means of a combination of SI and PSS tuning.

5.4 2050 Network

The main upgrades to the network from 2030 to 2050 are described in subsection 0. Regarding RES, 15 Doubly-Fed Induction Generators (DFIG) wind farms have been installed and their location is shown in Figure 171. Furthermore, 53 BESS units have been installed, in the 18 synchronous generator substations, the 20 FCWT substations and in the 15 DFIG wind farms substations (Figure 172). The rated power of each battery/converter unit has been set equal to 20 % of the rating of the close-connected plant, so to match the values reported by T.1.1 data.

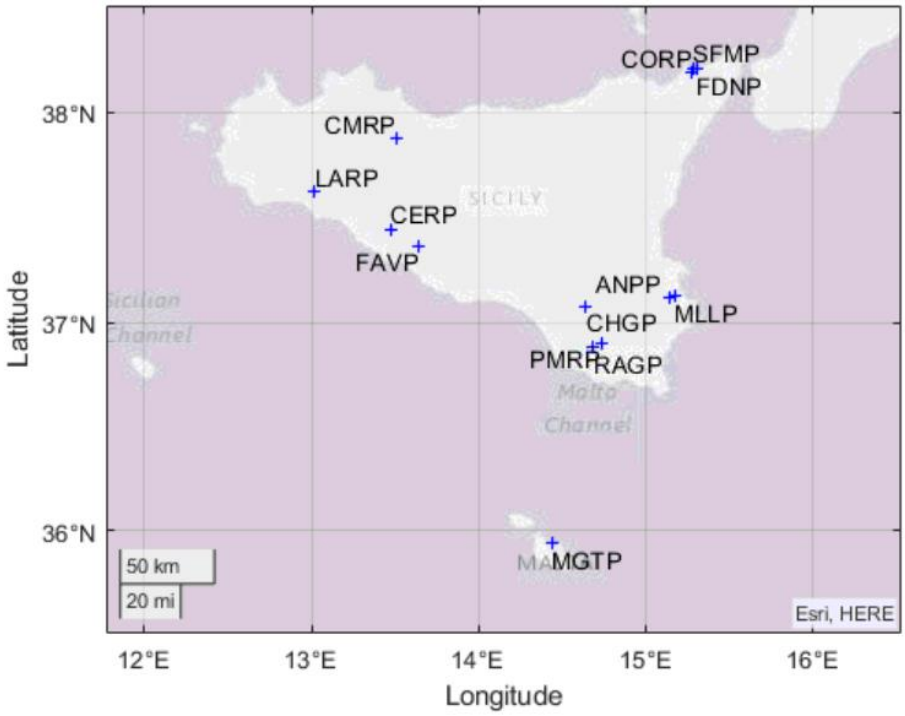

Figure 171. Locations of the DFIGs substations in the 2050 network.

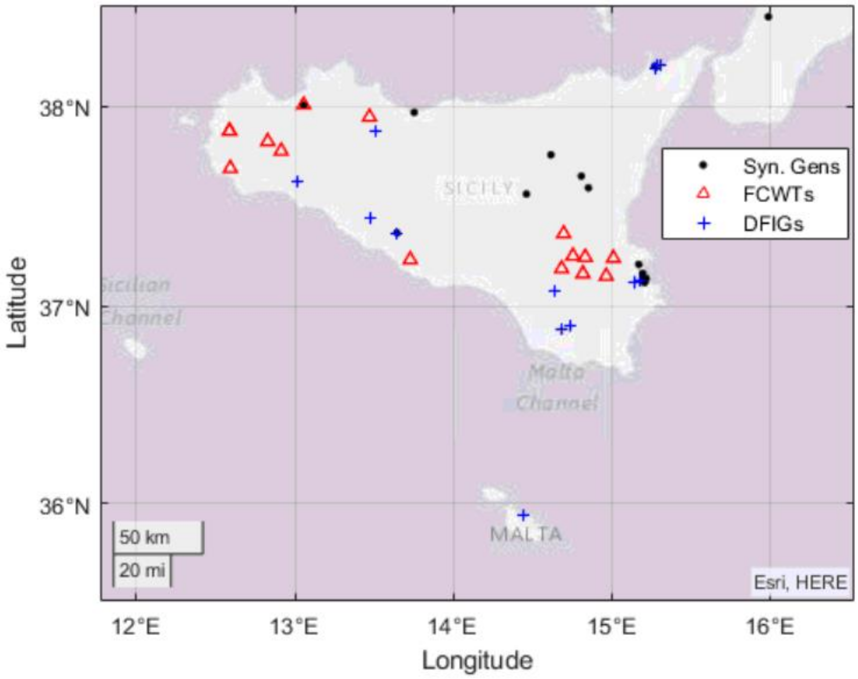

Figure 172. Locations of the synchronous generators, the FCWTs, and the DFIGs substations in the 2050 network.

5.4.1 Base case

5.4.1.1 High Export dispatching profile

In the 2050 *High Export* dispatching profile, all electromechanical modes have a damping ratio greater than 10% hence present no damping concerns.

5.4.1.2 High Import dispatching profile

For the *High Import* dispatching profile, the modal analysis revealed twenty oscillatory modes, including with a damping ratio above 5% and below 10%, fifteen of which (modes D1 to D15) involve DFIG units. Of the remaining five modes, four have been already encountered and examined in the 2030 network while mode M8, with a damping ratio very close to 10%, has not been discussed yet. The results are reported in Table 29.

Mode	Eigenvalues	Frequency, f (Hz)	Damping, ζ (%)	Involved Units/Plants
M1	-0.27 ± 4.81j	0.77	5.66	TIMP, PRGP, SLACK
D1	-0.67 ± 11.29j	1.80	5.90	DFIGs in ANPP
M2	-0.59 ± 8.18j	1.30	7.24	EGSP, PRGP
M4	-0.88 ± 9.98j	1.59	8.83	EGSP
M5	-0.89 ± 9.97j	1.59	8.90	EGSP
M8	-1.04 ± 10.44j	1.66	9.91	DITP, ESSP, PRGP

Table 29. Electromechanical modes in order of increasing damping ratio and below the threshold of 10%, for the 2050 High Import dispatching profile.

Following the procedure already used for the 2030 network, it is possible to identify the characteristics and the generators involved, by looking at their oscillation vectors. Modes M1, M2, M4 and M5 have been already identified in the 2030 network and their properties are discussed in section 5.3. The characteristics of D1 and M8 are:

- D1: In Figure 173 the oscillation vector of mode D1 is shown. This mode involves two DFIG units located in the substation of Anapo (ANPP). In total, there are 15 modes like this one and they involve the 15 DFIG wind farms in the network. Since these modes behave all very similarly, for the sake of conciseness, we will examine just the first one. Mode D1 is a local mode in which the speed of the DFIG unit ANPP2 oscillates against the DFIG unit ANPP3. The *High Import* profile is characterized by low wind production; as a result, the production of each 1.5MW rated DFIG unit has been set to 0.1MW. In order to analyse the characteristics of this mode, four different wind turbine power setpoints i.e., P = [0,0.1,0.2,0.3] MW, are considered and the effects on D1 are presented in Table 30. While the frequency of D1 does not appear to be correlated with the active power setpoint, the damping ratio of D1 is dependent on the active power injected by the wind turbine into the grid. Its value stays always above the 5% threshold and increases above 10% for active power production greater than 0.1 MW that is, around 7% of the rated power;
- M8: In Figure 174 the oscillation vector of mode M8 is shown. This is a local mode in which the 22.8 MVA generator in Dittaino (DITP) and the 58.1 MVA generator in Augusta (ESSP2), both not equipped with PSS, oscillate against the larger generator located in Priolo Gargallo, PRGP1, with a rated power of 370 MVA, a large constant of inertia of 7.5 s and equipped with PSS. For this reason, the magnitude of the oscillation vector of PRGP1 effectively appears like a dot in the origin.

Active Power setpoint [MW]	D1	
	f (Hz)	ζ (%)
0	1.80	6.1
0.1	1.80	5.9
0.2	✓	✓
0.3	✓	✓

Table 30. Effect of the DFIG active power production on mode D1.

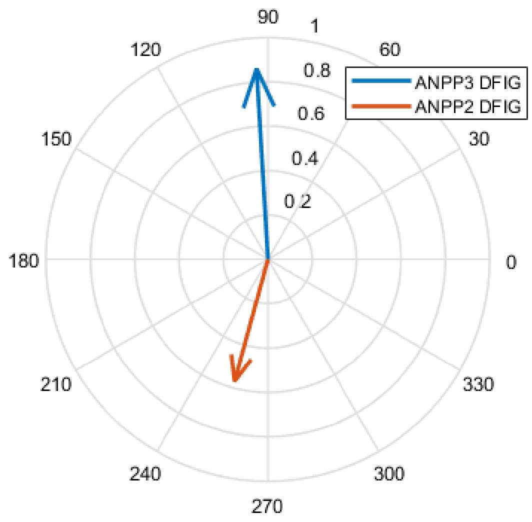

Figure 173. Oscillation vector of mode D1.

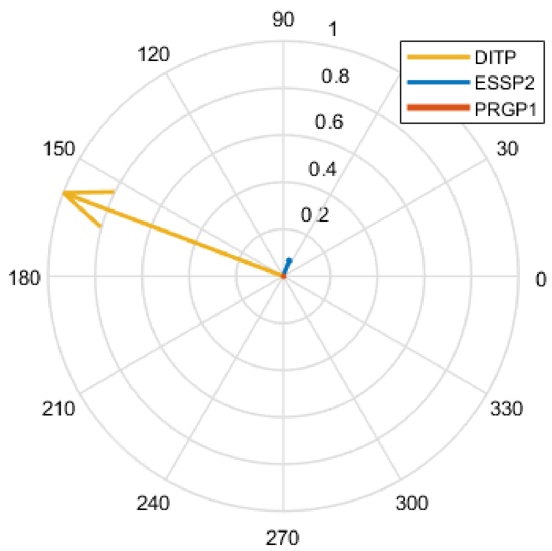

Figure 174. Oscillation vector of mode M8.

5.4.1.3 High Load dispatching profile

In the *High Load* dispatching profile, all oscillatory modes present a damping ratio greater than 10% hence it does not pose any stability concerns regarding small perturbations.

5.4.1.4 Low Load dispatching profile

In the *Low Load / Low Gas* dispatching profile, the modal analysis revealed 3 electromechanical modes with a damping ratio below 10% one of which, inter-area mode M1, with an unacceptable value of 3.88%. The results are reported in Table 31. As it will be shown, the inter-area mode can be properly damped either with the contribution of synthetic inertia provided by RES (contribution of both FCWT and BESS) or by tuning the gain of the relevant PSS, or by a combination of both.

Mode	Eigenvalues	Frequency, $f\ (Hz)$	Damping, ζ (%)	Involved Plants
M1	-0.19 ± 4.95j	0.79	3.88	TIMP, PRGP, SLACK
M9	-0.80 ± 10.86j	1.73	7.38	CNTP, PRGP
M10	-0.85 ± 11.09j	1.77	7.67	PATP, CNTP

Table 31. Modes with a damping ratio below 10% for the 2050 Low Load / Low Gas dispatching profile.

Modes M9 and M10 are two modes that did not previously appear, their properties are hereby discussed.

- M9: In Figure 175 the oscillation vector of mode M9 is shown. In this mode the relatively small generator in Contrasto (CNTP, 24 MVA) oscillates against the larger unit in Priolo Gargallo (PRGP1, 370 MVA) which, being also equipped with a PSS, is practically unaffected by the oscillations. For this reason, its oscillation vector is very small, and, in the graph, it appears like a point in the origin;
- M10: In Figure 176 the oscillation vector of mode M10 is shown. This mode involves the 9 MVA unit in Paternò (PATP) oscillating against the 24 MVA unit in Contrasto (CNTP), both without PSS.

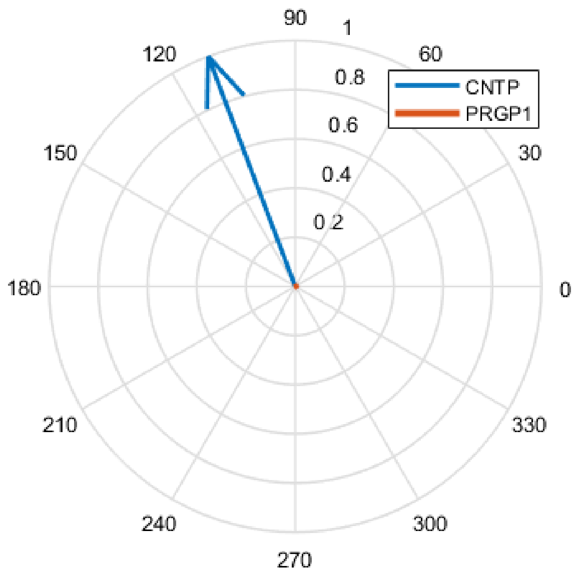

Figure 175. Oscillation vector of mode M9.

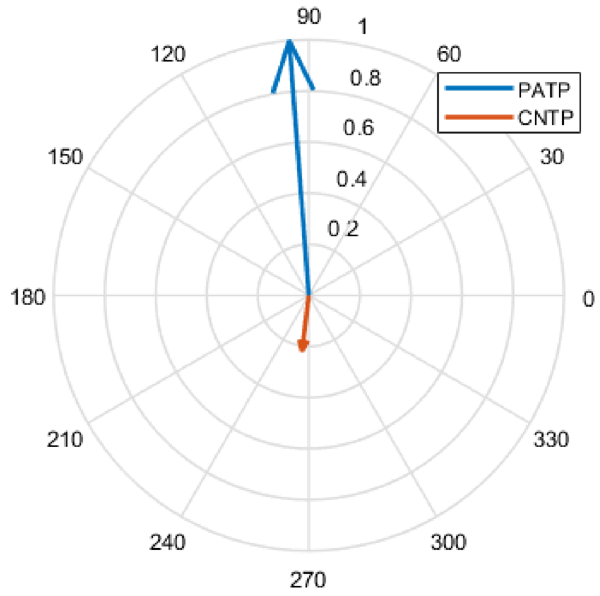

Figure 176. Oscillation vector of mode M10.

5.4.1.5 Island dispatching profile

In the *Island* dispatching profile, all oscillatory modes have a damping ratio greater than 10 %; hence, it does not present any stability concerns regarding small perturbations.

5.4.1.6 Lines out of service dispatching profile

In the *Line out of service* dispatching profile, the modal analysis presents the same modes of the *Low Load* one. The results are presented in Table 32. This dispatching profile is a variation of the *Low Load* one, in which two important 230 kV lines (lines Favara-Chiaramonte and Caracoli-Sorgente) are out of service. For this reason, the damping ratio of mode M1 decreases from the value of 3.88 % (*Low Load* dispatching profile) to a value of 1.08 %. Mode M1 is particularly affected here because the line Caracoli-Sorgente basically connects the plant in Termini Imerese (TIMP) to the interconnection with continental Italy, right before the substation of Rizziconi. Like for the *Low Load* dispatching profile, a combination of synthetic inertia support schemes and PSS tuning it is going to be adopted to properly damp the critical inter-area mode. Modes M9 and M10, maybe because of the location of the plants involved which are not connected by the lines out of service, are beneficially affected in this dispatching profile and their damping ratio is increased.

Mode	Eigenvalues	Frequency, $f\ (Hz)$	Damping, ζ (%)	Involved Plants
M1	-0.05 ± 4.73j	0.75	1.08	TIMP, PRGP, SLACK
M9	-0.86 ± 10.82j	1.72	7.95	CNTP, PRGP
M10	-0.92 ± 11.05j	1.76	8.26	PATP, CNTP

Table 32. Modes with damping ratio below 10% for the 2050 Lines out of service dispatching profile.

5.4.2 RES contribution and PSS tuning

Following the same procedure used for the 2030 network, in this section, the contribution of renewable energy sources to the small perturbation stability is evaluated and the relevant PSSs tuned. At first, the contribution of FCWT, BESS, and PSS tuning are analysed individually and then their combined effect is investigated.

5.4.2.1 Full Converter Wind Turbine Synthetic Inertia

This section aims at determining the contribution of DC-link-based inertia response (IR) provided by the FCWT units. The initial setting of the inertial response gain K_{IRF} is 0; then, its value is gradually increased to 50 by steps of 10 i.e., $K_{IRF} =$ [0, 10, 20, 30, 40, 50]. The modal analysis is then repeated for each value of K_{IRF} and for all the dispatching profiles:

- For the *High Export*, *High Load* and *Island* profiles, the presence or absence of IR provided by FCWT does not influence the results reported for the base case. That is, no mode with a damping below 10 % is detected;
- For the *High Import* dispatching profile, the results are shown in Table 33. Increasing the gain K_{IRF} **provides a significant improvement to the damping ratio** of mode M1. M2 and M8 experience a minor decrease in damping with increasing values of K_{IRF}. D1, M4 and M5 are not affected by K_{IRF};
- For the *Low Load* profile, the results are presented in Table 33. **Increasing values of K_{IRF} provide a significant improvement to the damping ratio of mode M1, making it properly damped**, a slight detrimental effect on mode M9 and no effect whatsoever on M10;
- For the **Lines out of service** dispatching profile, the results are reported in Table 34. **Increasing values of K_{IRF} provide a significant improvement to the damping ratio of mode M1, making it properly damped**, until the value of K_{IRF} reaches 30, then the damping ratio of M1 gets worst. The effect on the other two modes is the same as of in the *Low Load* one.

It must be noted that, regarding the *Low Load* and the *Lines out of service* dispatching profiles, the IR provided by FCWT is able to improve the damping ratio of inter-area mode M1 above the 5 % threshold but can do so just by a small margin. For a K_{IRF} value of 30, in the *Low Load* dispatching profile the damping ratio increases to a value of 5.18 % and to a value of 5.17 % in the *Lines out of service* dispatching profile. For this reason, in order to guarantee a more comfortable margin, other measures must be implemented. As shown in the following, tuning the PSS of the plants mainly involved in mode M1 allows increasing this margin to a more comfortable level. On the other hand, in this case, the BESS frequency support provides just a minor contribution.

K_{IRF}	M1		D1		M2		M4		M5		M8	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
0	0.77	5.66	1.80	5.9	1.3	7.24	1.59	8.83	1.59	8.90	1.66	9.91
10	0.77	5.67	1.80	5.9	1.3	7.23	1.59	8.83	1.59	8.90	1.66	9.91
20	0.77	7.19	1.80	5.9	1.3	7.11	1.59	8.83	1.59	8.90	1.66	9.72
30	0.77	7.39	1.80	5.9	1.3	7.07	1.59	8.83	1.59	8.90	1.66	9.69
40	0.78	7.40	1.80	5.9	1.3	7.05	1.59	8.83	1.59	8.90	1.67	9.67
50	0.78	7.35	1.80	5.9	1.3	7.03	1.59	8.83	1.59	8.90	1.67	9.66

Table 33. Effect of increasing inertial response contribution from FCWT on the modes of the High Import dispatching profile.

K_{IRF}	M1		M9		M10	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
0	0.79	3.88	1.73	7.38	1.77	7.67
10	0.79	4.37	1.73	7.34	1.77	7.67
20	0.79	4.87	1.73	7.32	1.77	7.67
30	0.79	5.18	1.73	7.30	1.77	7.67
40	0.79	5.31	1.73	7.29	1.77	7.67
50	0.79	5.37	1.73	7.28	1.77	7.67

Table 34. Effect of increasing inertial response contribution from FCWT on the modes of the Low Load dispatching profile.

K_{IRF}	M1		M9		M10	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
0	0.75	1.08	1.72	7.95	1.76	8.26
10	0.75	3.00	1.72	7.92	1.76	8.27
20	0.76	4.68	1.73	7.90	1.76	8.27
30	0.77	5.17	1.73	7.88	1.76	8.27
40	0.78	5.06	1.73	7.87	1.76	8.27
50	0.78	4.85	1.73	7.87	1.76	8.27

Table 35. Effect of increasing inertial response contribution from FCWT on the modes of the Lines out of service dispatching profile.

5.4.2.2 BESS Primary Frequency Response and Inertia Response

In this subsection, the contribution of Inertia Response (IR) and Primary Frequency Response (PFR) provided by the BESS units to the small perturbation angle stability of the network are investigated. The frequency controller of the BESS has been modified to respond to two input signals, namely frequency deviation and RoCoF as shown in Figure 177. Four different combinations of the PFR and IR gains are adopted, i.e., 20 and 100 for K_{PFRB} and 0 and 50 for K_{IRB}. Regarding K_{PFRB}, these values correspond to decreasing the droop from 5 % to 1 %. The base case settings of the BESS frequency controller included just the PFR contribution, i.e. (K_{PFRB}, K_{IRB}) = (20,0), and correspond to a droop of 5% and no inertial response. The modal analysis is repeated for each dispatching profile and the results are hereby discussed.

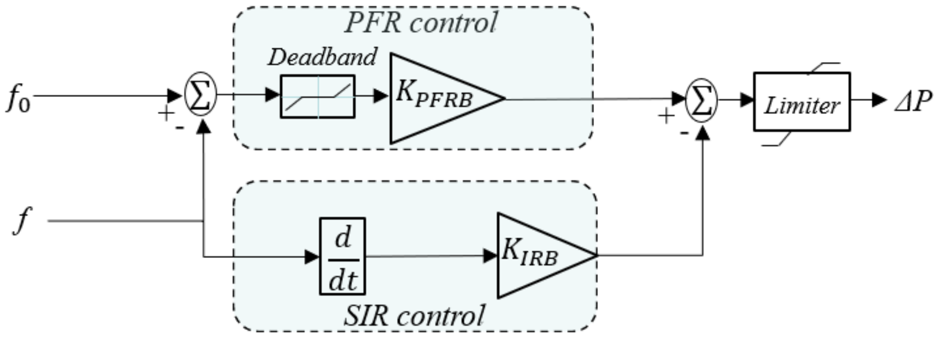

Figure 177. Frequency controller of the BESS providing both Primary Frequency Response (PFR) and Inertial Response services.

- For the *High Export*, *High Load* and *Island* dispatching profiles, the variation in value of the gains of the frequency support scheme does not introduce any mode with a damping ratio below 10 %. That is, the results presented for the base case remain unchanged;
- For the *High Import* dispatching profile, the results are presented in Table 36. Increasing the PFR component of the frequency support scheme from a value of 20 to a value of 100 that is, reducing the droop from 0.05 to 0.01, has little to no effect on the modes. Regarding the inertial response component, high values of the gain K_{IRB} produce minor to no effect on modes D1 to D15, while the damping ratios of modes M2, M4, M5 and M8 are significantly improved above the threshold of 10 %;
- For the *Low Load* dispatching profile, the results are presented in Table 36. Like for the *High Import* one, the PFR component of the frequency support scheme, would produce little to no effect on the examined modes. Regarding the inertial component, higher values of K_{IRB} provide a minor improvement in the damping of mode M1, but not enough to properly damp it, and little to no effect on M9 and M10;
- For the *Lines out of service* dispatching profile, the results are reported in Table 37. This is a variation of the *Low Load* one and the results are very similar. The PFR component does not produce any significant effect on the modes under consideration and increasing the gain K_{IRB} produces minor improvements to the damping of mode M1 and little to no effect on M9 and M10.

In conclusion, the PFR support scheme of the BESS is not able to provide a better damping to the electromechanical modes while the added IR branch is. However, this contribution is not sufficient, and it is not able to properly damp the critical mode M1.

(K_{PFRB}, K_{IRB})	M1		D1		M2		M4		M5		M8	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
(20,0)	0.77	5.66	1.80	5.9	1.3	7.24	1.59	8.83	1.59	8.90	1.66	9.91
(100,0)	0.77	5.66	1.80	5.9	1.3	7.24	1.59	8.83	1.59	8.90	1.66	9.91
(20,20)	0.77	5.69	1.80	5.9	1.3	8.59	1.59	9.40	1.59	9.47	✓	✓
(20,50)	0.77	5.74	1.80	5.9	✓	✓	✓	✓	✓	✓	✓	✓

Table 36. Change in frequency and damping ratio of the electromechanical modes for increasing values of the gains K_{PRFB} and K_{IRB} related to the frequency support provided by BESS in the High Import dispatching profile.

(K_{PFRB}, K_{IRB})	M1		M9		M10	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
(20,0)	0.79	3.88	1.73	7.38	1.77	7.67
(100,0)	0.79	3.88	1.73	7.38	1.77	7.67
(20,20)	0.79	3.90	1.73	7.39	1.77	7.67
(20,50)	0.79	3.92	1.73	7.39	1.77	7.67

Table 37. Change in frequency and damping ratio of the electromechanical modes for increasing values of the gains K_{PRFB} and K_{IRB} related to the frequency support provided by BESS in the Low Load dispatching profile.

(K_{PFRB}, K_{IRB})	M1		M9		M10	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
(20,0)	0.75	1.08	1.72	7.95	1.76	8.26
(100,0)	0.75	1.08	1.72	7.95	1.76	8.26
(20,20)	0.75	1.13	1.72	7.96	1.76	8.26
(20,50)	0.75	1.22	1.72	7.96	1.76	8.26

Table 38. Change in frequency and damping ratio of the electromechanical modes for increasing values of the gains K_{PRFB} and K_{IRB} related to the frequency support provided by BESS in the Lines out of service dispatching profile.

5.4.2.3 BESS Location

The influence of the primary frequency response of the BESS on the modes was found to be not significant. However, the inertial response scheme implemented on the BESS provided improvement on some of the modes. In this section, the 53 locations previously considered have been split into two sets, i.e., the BESS located in the synchronous generator substations and the BESS located in the Wind farm substations, and the contribution of the two sets have been considered separately, in order to highlight the contribution to the damping of electromechanical modes. The 53 BESS units are installed one in each of the substations of the 18 synchronous generator (referred to as “synchronous generator location”) and one in each of the 35 wind farm substations (15 DFIG and 20 FCWT) referred to as “wind farm location”. In the previous case, about the PFR and IR effect on the electromechanical modes, the support from all the BESS in all the 53 locations has been simultaneously considered.

In this study, the two different type of locations will be considered individually. The effect of PFR and IR from the two different locations are studied for four different combinations of PFR and IR gains. Specifically, attention is given to the IR from the BESS, since it has been shown from the previous section that only the IR has positive influence on the modes. The modal analysis is repeated just for the *High Import* dispatching profile since, as seen in the previous subsection, it was the most sensitive to BESS IR. The results are shown in Table 39 and Table 40.

For the case of BESS units installed just in the synchronous generator locations, the PFR component provided by K_{PFRB} has no detectable effect on the modes. On the other hand, higher values of the inertial component gain K_{IRB} provided minor improvements to the damping of M1 and no effect on modes D1 to D15. Most significantly, the damping ratios of M2, M4, M5 and M8 are increased well above the conservative threshold of 10 %.

For the case of BESS units installed just in wind farm locations, acting on the PFR component that is, lowering the droop from 5 % to 1 %, has no detectable effect on the modes. Regarding, inertial response, higher values of the gain K_{IRB} provide minor improvements to the stability of M1 and M2 and no effect on D1 to D15. The damping ratios of M4, M5 and M8 are not affected with all possible gain combinations.

This goes to show that electromechanical modes with low damping can be improved by SI support schemes implemented on units installed near the participating synchronous generators.

(K_{PFRB}, K_{IRB})	M1		D1		M2		M4		M5		M8	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
(20,0)	0.77	5.66	1.80	5.9	1.3	7.24	1.59	8.83	1.59	8.90	1.66	9.91
(100,0)	0.77	5.66	1.80	5.9	1.3	7.24	1.59	8.83	1.59	8.90	1.66	9.91
(20,20)	0.77	5.67	1.80	5.9	1.3	8.58	1.59	9.44	1.59	9.47	✓	✓
(20,50)	0.77	5.69	1.80	5.9	✓	✓	✓	✓	✓	✓	✓	✓

Table 39. Influence on the modes of the High Import dispatching profile of BESS frequency support considering only synchronous generator locations.

(K_{PFRB}, K_{IRB})	M1		D1		M2		M4		M5		M8	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
(20,0)	0.77	5.66	1.80	5.9	1.3	7.24	1.59	8.83	1.59	8.90	1.66	9.91
(100,0)	0.77	5.66	1.80	5.9	1.3	7.24	1.59	8.83	1.59	8.90	1.66	9.91
(20,20)	0.77	5.69	1.80	5.9	1.3	7.24	1.59	8.83	1.59	8.90	1.66	9.90
(20,50)	0.77	5.72	1.80	5.9	1.3	7.25	1.59	8.83	1.59	8.90	1.66	9.90

Table 40. Influence on the modes of the High Import dispatching profile of BESS frequency support considering only the wind farm locations.

5.4.2.4 PSS gain tuning

Following the procedure used for the 2030 network, in this subsection the effect of the PSS gain on the electromechanical modes with damping below 10 % is independently investigated. Specifically, the effect on inter-area mode M1 that has not been well satisfactorily damped by the contribution provided by FCWT and BESS will be the focus. Since the plant in Termini Imerese (TIMP) is the one with the highest participation factor in inter-area mode M1, only its PSS gain is tuned while the others are kept unchanged. For the TIMP generators the values of K_{PSS} = [0, 0.5, 1, 2, 3] p.u. are adopted, the modal analysis is repeated for each dispatching profile and the effect on the electromechanical modes is examined.

For the *High Import* case, the results are presented in Table 41. Values of K_{PSS} above 1 p.u. are not beneficial for the damping ratio of inter-area mode M1. Increasing the value of the gain, a minor increase to the damping ratio of M2 and M8 is observed, whereas modes D1, M4 and M5 are unaffected by it. In absence of PSS, that is for K_{PSS} equals to 0, mode A6 drops below the 10 % damping threshold with a frequency of 1.47 Hz and damping ratio of 9.18 %.

K_{PSS} of TIMP (p.u.)	M1		D1		M2		M4		M5		M8		A6	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
0	✓	✓	1.80	5.9	1.3	7.20	1.59	8.83	1.59	8.90	1.66	9.84	1.47	9.18
0.5	✓	✓	1.80	5.9	1.3	7.24	1.59	8.83	1.59	8.90	1.66	9.85	✓	✓
1	✓	✓	1.80	5.9	1.3	7.24	1.59	8.83	1.59	8.90	1.66	9.86	✓	✓
2	0.80	8.85	1.80	5.9	1.3	7.23	1.59	8.83	1.59	8.90	1.66	9.89	✓	✓
3	0.77	5.66	1.80	5.9	1.3	7.24	1.59	8.83	1.59	8.90	1.66	9.91	✓	✓

Table 41. Effect on the modes of the High Import dispatching profile for increasing values of the PSS in TIMP.

For the *Low Load* dispatching profile, the results are presented in Table 42. Keeping in mind that the generators mainly involved in modes M9 and M10, CNTP and PAPT respectively, are not equipped with PSS, it appears clear how tuning the PSS in TIMP produces mainly a beneficial effect on mode M1. Increasing the value of the gain, the frequency of mode M1 steadily decreases while, at a K_{PSS} value of 0.5 p.u., the damping ratio reaches it maximum value of 8.25 %. A minor increase in the damping ratio of M9 is observed whereas M10 is unaffected. At K_{PSS} of 0, mode A7 drops below the 10 % damping threshold with a frequency of 1.19 Hz and damping ratio of 7.6 %.

K_{PSS} of TIMP (p.u.)	M1		M9		M10		A7	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
0	1.00	7.27	1.73	7.34	1.77	7.67	1.19	7.59
0.5	0.95	8.25	1.73	7.35	1.77	7.67	✓	✓
1	0.91	7.98	1.73	7.36	1.77	7.67	✓	✓
2	0.84	6.19	1.73	7.37	1.77	7.67	✓	✓
3	0.79	3.88	1.73	7.38	1.77	7.67	✓	✓

Table 42. Effect on the modes of the Low Load dispatching profile for increasing values of the PSS in TIMP.

For the line out of service dispatching profile, the results are shown in Table 43. The results are similar to the *Low Load* one: both the frequency and damping ratio of M1 decrease for increasing values of the gain. For a K_{PSS} value of 0.5 p.u the damping ratio of M1 is equal to 6.55 % and for a K_{PSS} value of 1 p.u is equal to 5.7 %. A minor decrease in the damping ratio of mode M9 is observed whereas M10 is unaffected. Without PSS, mode A7 drops below the 10 % damping threshold with a frequency of 1.19 Hz and damping ratio of 7.7 %.

K_{PSS} of TIMP (p.u.)	M1		M9		M10		A7	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
0	0.91	6.95	1.72	7.92	1.76	8.26	1.19	7.69
0.5	0.87	6.55	1.72	7.93	1.76	8.26	✓	✓
1	0.84	5.70	1.72	7.93	1.76	8.26	✓	✓
2	0.79	3.58	1.72	7.94	1.76	8.26	✓	✓
3	0.75	1.08	1.72	7.95	1.76	8.26	✓	✓

Table 43. Effect on the modes of the Lines out of service dispatching profile for increasing values of the PSS in TIMP.

Concluding, it has been found that a PSS gain value of the TIMP units ranging from 0.5 to 1 p.u. is the best solution. It provides satisfactory damping to inter-area mode M1 without compromising the stability of other modes. Regarding modes M9 and M10, they are not significantly affected, and their damping ratio is well above 5 %. If their damping ratio needs to be increased above the conservative threshold of 10 %, a possible suggestion is to make an exception and equip also the small units involved in those modes, CNTP and PAPT, with a PSS.

5.4.2.5 Combined influence of Frequency Support Schemes of BESS, FCWT and PSS tuning

In this subsection, we conclude by combining all the different aspects analysed so far. The combined influence of PSS and frequency support schemes provided by FCWT and BESS is investigated.

- For the BESS units, PFR and IR gain combination of (K_{PFRB}, K_{IRB}) = (20,50) p.u. is adopted;
- For the FCWT units, the SI gain value of K_{IRF} = 30 p.u. is adopted;
- For the PSS units of synchronous generators at TIMP, gain of K_{PSS} = 1 p.u is adopted.

The results reported in the following tables show that a combined effort from RES and PSS allows for a very good damping of oscillations with all the modes having a damping ratio above 5 % and most of the modes above the conservative threshold of 10 %. In particular, this is true for the critical inter-area mode M1. For the *High Import* dispatching profile, the results are presented in Table 44.

Case	M1		D1		M2		M4		M5		M8	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
Base	0.77	5.66	1.80	5.9	1.3	7.24	1.59	8.83	1.59	8.90	1.66	9.91
Optimum	✓	✓	1.80	5.9	✓	✓	✓	✓	✓	✓	✓	✓

Table 44. Comparison between the base case and the combined contribution of RES frequency support and PSS tuning to the small signal stability for the High Import dispatching profile.

For the *Low Load* dispatching profile, the results are presented in Table 45. It can be seen how, with a combined effort, the critical inter-area mode is properly stabilized and damped above the 10 % threshold. On the other hand, modes M9 and M10, due to the size and the location of the plants involved, are not significantly affected, but maintain a damping ratio above 5 %.

Case	M1		M9		M10	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
Base	0.79	3.88	1.73	7.38	1.77	7.67
Optimum	✓	✓	1.73	7.30	1.77	7.68

Table 45. Comparison between the base case and the combined contribution of RES frequency support and PSS tuning to the small signal stability for the Low Load dispatching profile.

For the line out of service dispatching profile, the results are presented in Table 46. This dispatching profile is a variation of the *Low Load* one and the conclusions are very similar.

Case	M1		M9		M10	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
Base	0.75	1.08	1.72	7.95	1.76	8.26
Optimum	✓	✓	1.73	7.88	1.76	8.27

Table 46. Combined contribution of RES frequency support and PSS tuning to the small signal stability for the Lines out of service dispatching profile.

5.4.3 2050 Conclusions

The small perturbation stability of the power system of Sicily, forecasted for the year 2050, has been here analysed in the six different dispatching profiles identified:

- High Export;
- High Import;
- High Load;
- Island;
- Low Load;
- Lines out of service.

Like for 2030, in each profile, the modal analysis has been performed focusing on the modes with a damping ratio below 10 %, being the conservative threshold, and 5 % being the critical one.

For the base case 2050 analysis, in which RES support frequency control is not active, it has been found that the *Low Load* and the *Lines out of service* dispatching profiles present one low damped electromechanical mode. This mode is the **inter-area mode** between the equivalent generator in Rizziconi and the power plant near Termini Imerese and, as for 2030, it has been shown how **its damping can be improved thanks to the contribution of synthetic inertia provided by wind farms, BESS and by tuning the PSS of relevant generators**.

The *High Export*, *High Load* and *Island* dispatching profiles do not present any electromechanical modes with damping ratio below 10 %. The *High Import* one presents 20 electromechanical modes, 15 of which involve the DFIG units present in the system; these modes have all a damping ratio ranging from 5 % to 10 % and their damping ratio can be further increased thanks to the contribution of synthetic inertia provide by RES.

Like in the 2030 network, also in 2050 the Sicilian grid shows good damping of oscillations. Furthermore, compared to the 2030 network, the grid displays a larger variety of tools to tackle frequency instabilities.

6 Voltage stability analysis

This last chapter summarizes the results identified by ENSiEL, in particular Politecnico di Milano, on the voltage stability analysis of the Sicilian grid on the same scenario and operating conditions already considered in previous chapters.

The voltage stability is a steady-state analysis (i.e., slow dynamics considered) aimed at identifying 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 [5]. The following are the principal causes of voltage instability:

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

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 renewable (RES) power plants have been assumed to be equipped with specific devices and controls, adopted by Terna in the Italian grid code [21][22][23], 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.

6.1 Procedure

To carry out the voltage stability analysis, the PV curve calculation has been used and adapted for this research. 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 monitored to fulfil the 0.9 - 1.1 p.u. limits.

Zero and negative loads have been not 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 have been reached.

Reactive support of the RES is also considered and the current capability limits given by Terna in [21][22] are used as reference (Figure 178, red solid line):

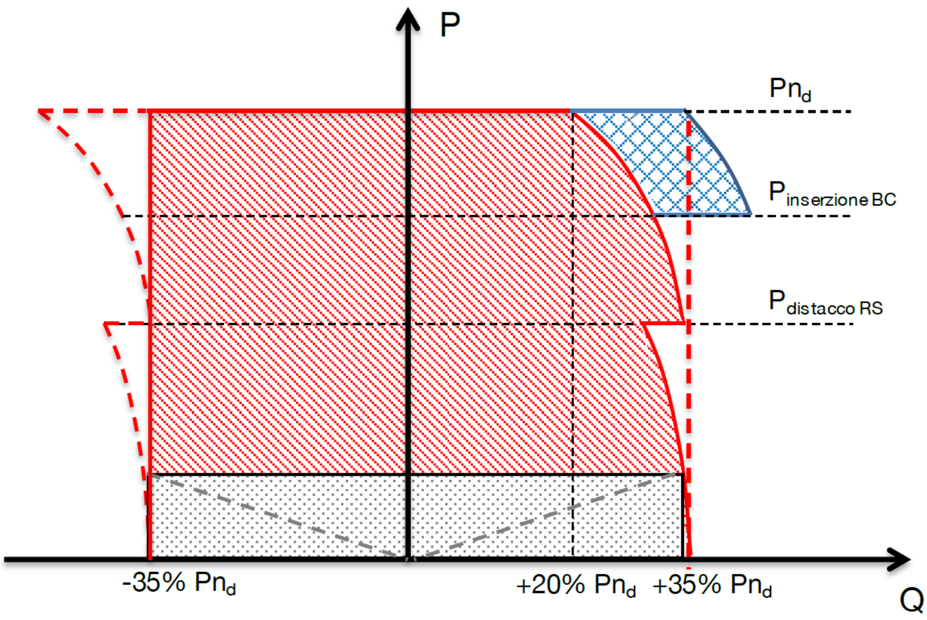

Figure 178. Capability curve implemented for wind and PV plants [21][22].

The maximum/minimum reactive support must be equal to the ± 35 % of the current active power available. Regarding the controller logic, the injection of reactive power depending on the voltage values is assumed to be in accordance with Figure 179, where $|\Delta V_{max}| = |\Delta V_{min}| = 0.05 * V_{nom}$:

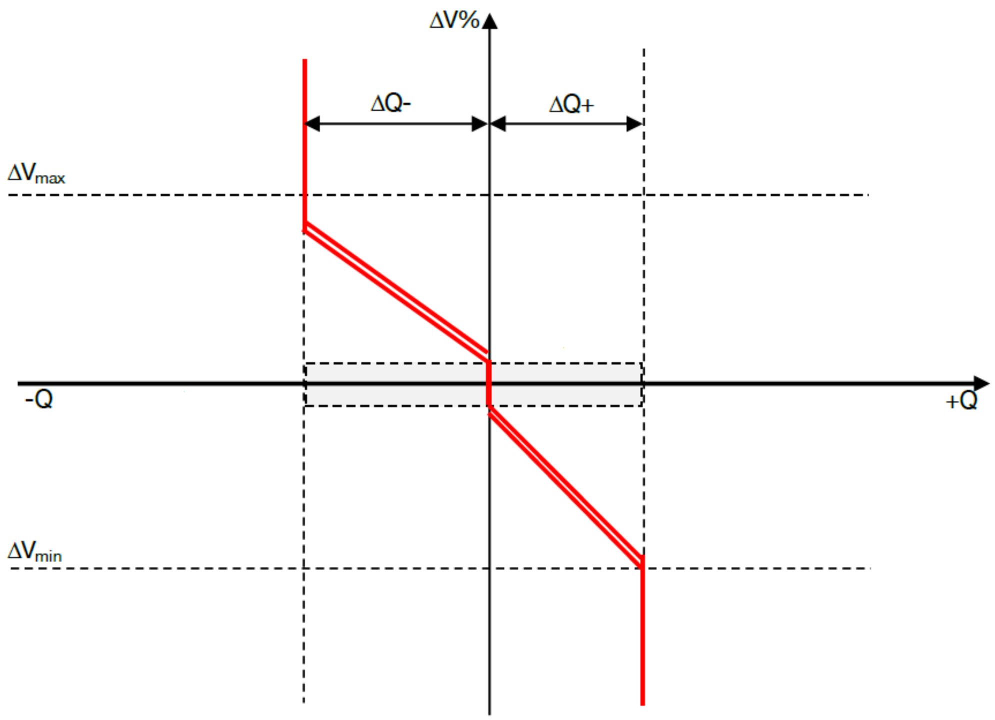

Figure 179. Q/V curve given by Terna in [21][22].

According to the annexes [21] and [22], the reactive droop has been set equal to 14 %:

$$droop = \frac{\Delta V}{\Delta Q} = \frac{|0.05|}{|0.35|} = 14\ \% \tag{8}$$

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 % will be considered acceptable as well.

6.2 2030 Network

All the 2030 dispatching profiles described in chapter 3 have been studied. First, the base case results are analysed, where **only the synchronous machines are assumed to provide the reactive support**; then, a second study has been performed, considering the reactive contribution given by the RES plants as well. The first analysis may be considered not realistic, since, according to the current Terna requirements [21][22][23], all the HV connected plants must participate to the voltage regulation, providing reactive power; however it is a worst case benchmark. These preliminary results are hence used as a first starting point for the subsequent assessments.
All the MV connected plants have to provide reactive power as well according to the CEI 0-16 Standard [23], but, since they are connected to the primary substations through MV feeders, a portion of their reactive contribution is exploited by the MV grid, and hence their overall effect on the HV grid cannot has to be assumed. To consider them into the analysis, the same limits of Figure 178, almost similar to the ones required by [23], have been adopted and a sensitivity analysis has been performed, changing their reactive power limits (the red solid lines reported in Figure 179), to analyse their reactive contribution to the primary substation, and therefore to the HV network. Hence, HV and MV RES plants have been equipped with the prescribed capability curve of Figure 178 and the second analysis has been performed.
All the analyses have been stopped as soon as the voltage profile of one single HV busbar goes below the lower 0.9 limit.

6.2.1 Base case

6.2.1.1 High Export dispatching profile

The voltage profiles of the 400 kV busbars of the *High Export* dispatching profile are shown in Figure 180, starting from the initial demand of 3096 MW; the maximum demand achievable is equal to 4876 MW, when a bus voltage goes below the 0.9 limit (blue line), since several synchronous machines reach their reactive capability limits and are no longer able to provide voltage support.

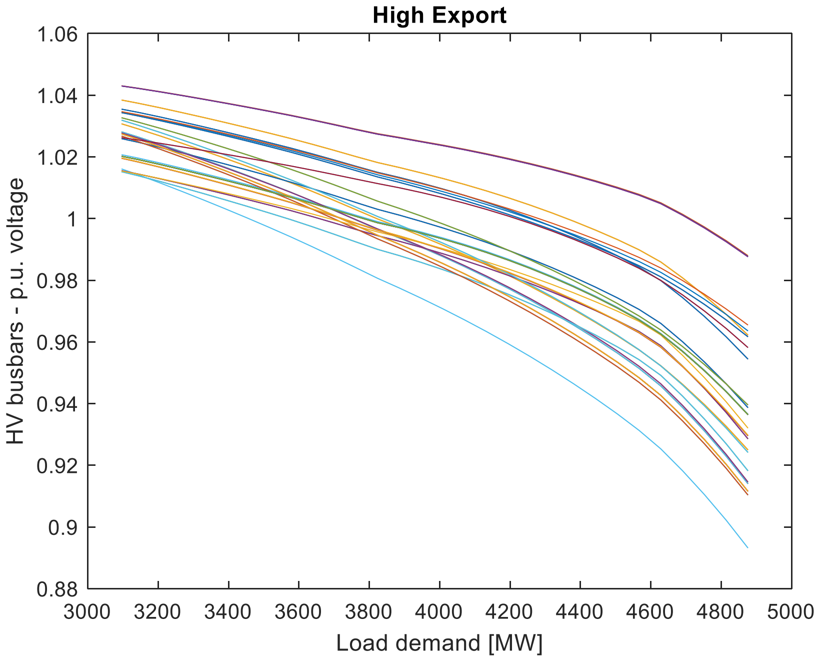

Figure 180. HV voltage profile of the High Export dispatching profile.

6.2.1.2 High Import dispatching profile

The voltage profiles of the 400 kV busbars of the *High Import* are shown in Figure 181, starting from the initial demand of 3070 MW: the maximum demand achievable is equal to 3790 MW, then multiple busbars are violating the lower limit.

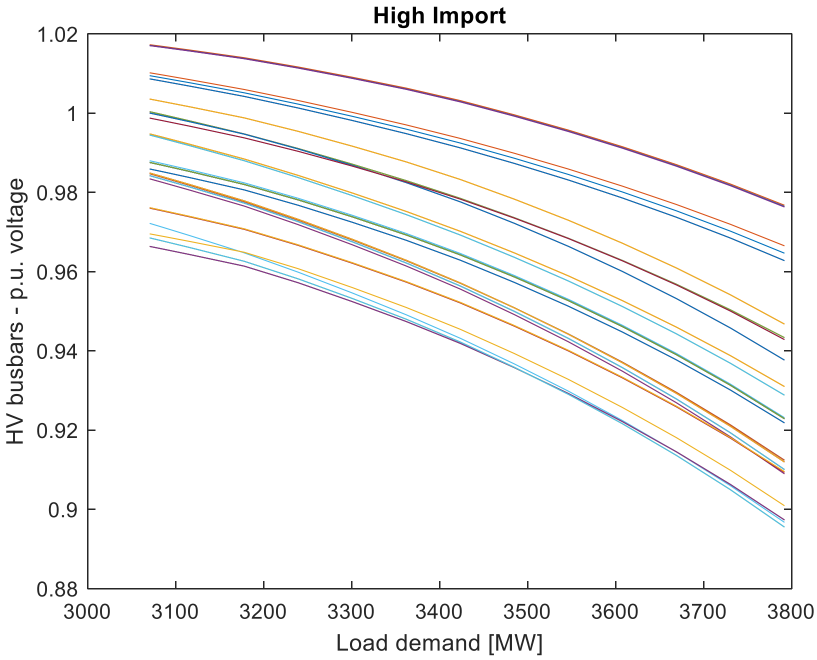

Figure 181. HV voltage profile of the High Import dispatching profile.

6.2.1.3 High Load dispatching profile

The voltage profiles of the 400 kV busbars of the *High Load* dispatching profile are shown in Figure 182, starting from the initial demand of 2945 MW; the maximum demand achievable is equal to 4636 MW.

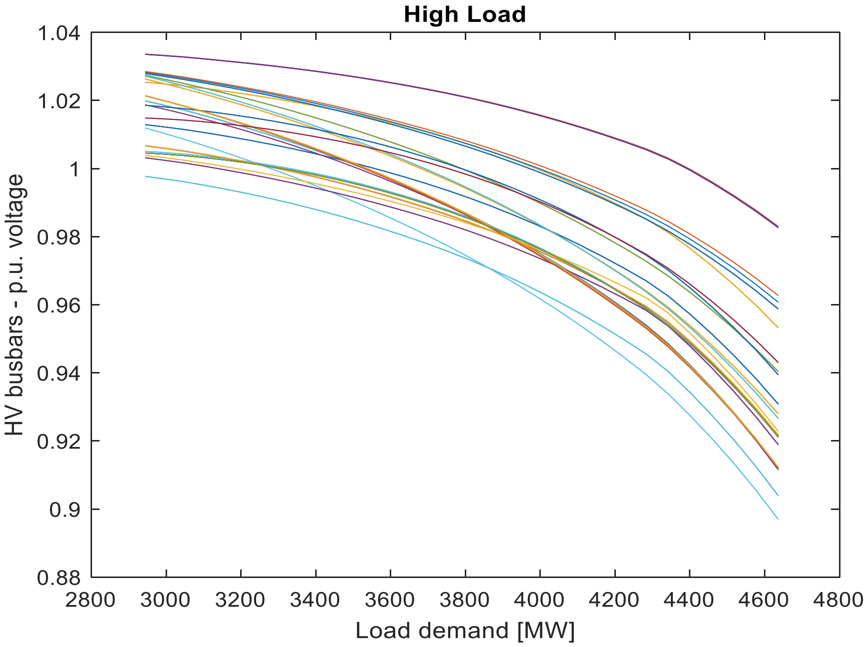

Figure 182. HV voltage profile of the High Load dispatching profile.

6.2.1.4 Low Load / Low Gas dispatching profile

The voltage profiles of the 400 kV busbars of the *Low Load* dispatching profile are shown in Figure 183, starting from the initial demand of 1840 MW; the maximum demand achievable is equal to 3856 MW.

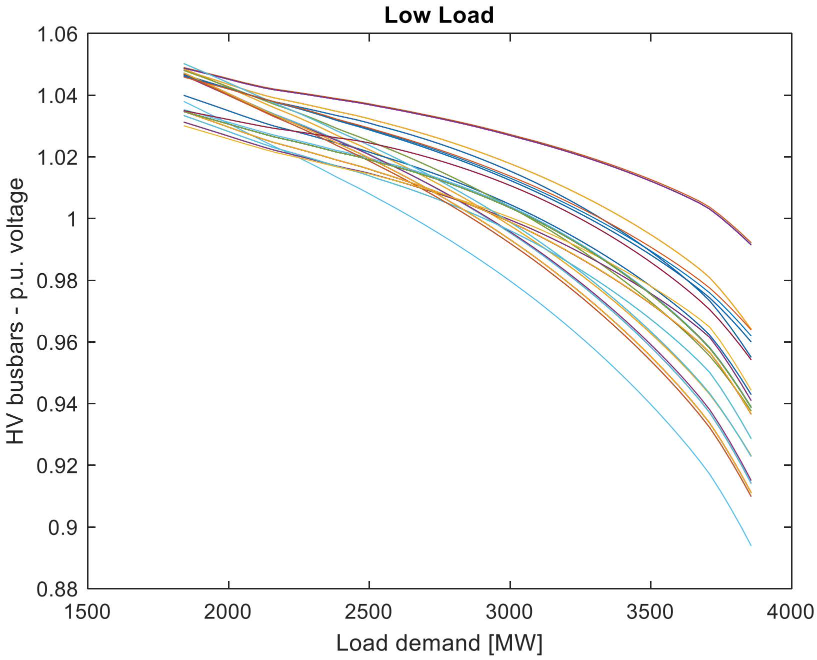

Figure 183. HV voltage profile of the Low Load dispatching profile.

6.2.1.5 Island dispatching profile

The voltage profiles of the 400 kV busbars of the *Island* dispatching profile are shown in Figure 184, starting from the initial demand of 2945 MW; the maximum demand achievable is equal to 4139 MW. Clearly, at the end of the curve, all the busbars present a sudden voltage decline, caused by almost all the synchronous machines reaching their maximum capability limits.

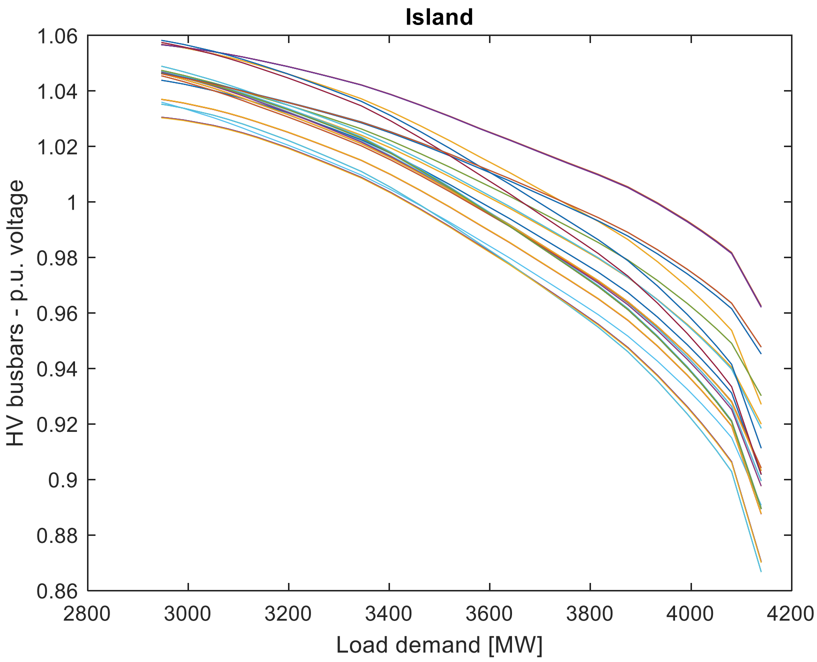

Figure 184. HV voltage profile of the Island dispatching profile.

Table 47 shows the reactive power limits of the active synchronous machines and their reactive production (load demand is equal to 4139 MW): several machines reached their maximum capability and cannot support any longer the voltage profile.

Generator	Lower reactive limit [Mvar]	Upper reactive limit [Mvar]	Current reactive production [Mvar]
CNTP	-8.96	22,00	21,99
EGNP1	-45.58	81,60	65.91
EGNP2	-40.20	81,60	3.55
EGNP3	-12.56	37,28	37,28
EGNP4	-14.56	37,28	37,28
EGSP1	-8,21	10,00	9,99
EGSP2	-8,21	10,00	9,99
EGPS3	-9,00	10,00	9,99
ESSP1	-19.69	43,60	43,59
ESSP2	-6,57	13,70	13,69
ISBP1	-48,73	117,00	91.98
ISBP2	-73.98	161,19	137.86
PRGP	-63.46	280,00	279,99
TEMP	-108.87	104,60	104,59
TIMP1	-78.95	230,40	230,39
TIMP2	-76.17	255,00	255,00

Table 47. Synchronous machines limits and current reactive production.

6.2.1.6 Lines out of service dispatching profile

The voltage profiles of the 400 kV busbars of the weak grid dispatching profile are shown in Figure 185, starting from the initial demand of 1840 MW; the maximum demand achievable is equal to 3525 MW.

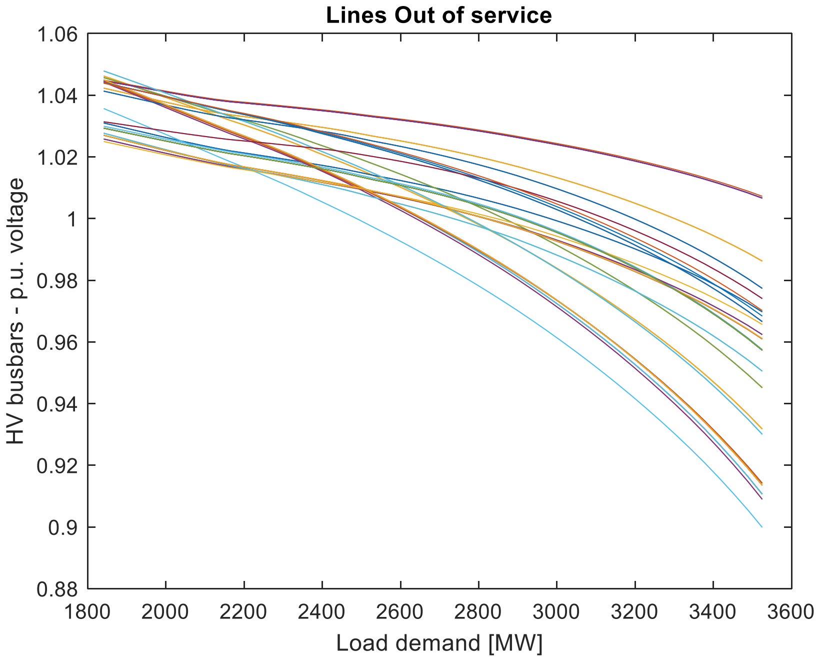

Figure 185. HV voltage profile of the dispatching profile with the 230 kV Lines out of service.

6.2.1.7 Summary of reactive support provided by synchronous generators only

The results are finally summarized in Table 48, along with the loadability margin in MW and percentage. It can be easily appreciated that the *High Import* dispatching profile presents a low loadability margin, less than 25 %; hence, additional resources should be used to increase voltage stability margins. All the other profiles present enough loadability margin, even if the *Island* one has showed a sudden voltage decline when the demand goes above 4100 MW, due to shortage of reactive resources.

Dispatching profile	Initial Load [MW]	Final Load [MW]	Loadability [MW]	Loadability [%]
High Export	3096	4876	1780	57.5
High Import	3070	3790	721	23.5
High Load	2945	4636	1692	57.5
Low Load	1840	3856	2015	109.5
Island	2945	4139	1193	40.5
Lines out of service	1840	3525	1684	91.5

Table 48. Loadability margins for the selected dispatching profiles for 2030.

6.2.2 RES contribution

Keeping the same active power demand, the reactive contribution of the RES has been considered in the voltage stability analysis. All the wind and photovoltaic plants connected to the HV grid have been provided with the reactive power controllers according to the current Italian standards as described in Section 6.1. The photovoltaic plants connected to the MV network, and representing the MV dispersed generation, have been modified to provide reactive power support as well. As previously explained, the MV connected plants should compensate the reactive request of the feeders under the primary substations, and hence, their overall effect on the HV is not explicitly considered in the model, but assumed by means of equivalent plants.

A first analysis with a “full” RES reactive contribution (according to the current requirements) from HV and MV plants has been performed, to check the effects on the network. Thanks to the reactive contribution of the RES plants, the loadability margin can be significantly increased: results are shown in Table 49. This offers more satisfactory results compared to the base case; in all the dispatching profiles the margin is increased, except for the one with the lines out of service, which was already good. This last profile already presents a good margin, but the interruption of the 230 kV ring circuit limits the reactive support. Concerning the *High Import* profile, its margin is almost doubled, reaching an acceptable level. In this dispatching profile, the RES contribution is provided by the HV wind plants only, as all the photovoltaic plants are out of service.

Dispatching profile	Final Load [MW]	Loadability [MW]	Loadability [%]	Loadability [%] without RES
High Export	5420	2324	75.1	57.5
High Import	4277	1207	40.0	23.5
High Load	6123	3178	108.0	57.5
Low Load	4069	2229	121.1	109.5
Island	4357	1412	47.9	40.5
Lines out of service	3556	1716	93.2	91.5

Table 49. Loadability margins for the selected dispatching profiles for 2030 with the full RES reactive contribution.

Regarding the sensitivity analysis of the MV plants, the reactive capability of the photovoltaic plants has been decreased, to consider the MV feeder loading, and the droop given by (8) has been set accordingly: first, the maximum/minimum reactive support of the MV plants has been limited to the 24 % of the current active power available (Table 50) and then to the 12 % (Table 51Table 50. Loadability margins for the selected dispatching profiles for 2030 with a medium MV RES reactive contribution.

).

As it can be seen, those dispatching profiles with a significant photovoltaic production from MV plants show a decrease on the loadability margin, but the overall level can be still considered acceptable, since most of the reactive power is provided by the RES plants connected to HV system. It can be observed that, as expected, MV plants may provide additional reactive support to the high voltage grid, but their impact is minimal compared to the reactive contribution of the HV connected plants.

Dispatching profile	Final Load [MW]	Loadability [MW]	Loadability [%]
High Export	5333	2237	72.2
High Import	4277	1207	40.0
High Load	5967	3022	102.6
Low Load	4069	2229	121.1
Island	4338	1393	47.3
Lines out of service	3556	1716	93.2

Table 50. Loadability margins for the selected dispatching profiles for 2030 with a medium MV RES reactive contribution.

Dispatching profile	Final Load [MW]	Loadability [MW]	Loadability [%]
High Export	5236	2140	69.1
High Import	4277	1207	40.0
High Load	5820	2875	97.6
Low Load	4069	2229	121.1
Island	4294	1349	45.8
Lines out of service	3556	1716	93.2

Table 51. Loadability margins for the selected dispatching profiles for 2030 with a low MV RES reactive contribution.

6.2.3 2030 Conclusions

The voltage stability of the power system of Sicily, forecasted for the year 2030, has been here analysed in the six different dispatching profiles identified:

1. High Export;
2. High Import;
3. High Load / Low Gas;
4. Island;
5. Low Load / Low Gas;
6. Lines out of service.

In each dispatching profile, the voltage stability of Sicily has been analysed. In particular, the critical point of voltage instability has been found increasing the active power demand of the loads until the power flow calculation no longer converges or some HV nodes goes below the under voltage limit of 0.9 p.u.

According to the Terna and CEI requirements, renewable energy sources connected to the grid through static converters have been equipped with a suitable capability curve in order to provide reactive support. Simulations have been first performed considering only the synchronous generators reactive contribution and then with the RES support.

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. 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.

It has been shown that **the reactive support of the renewable energy sources contributes to increase the overall loadability margin** in all the dispatching profiles.

As a conclusion for 2030, 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 presence of quite high-RES penetration, the voltage stability can be kept. MV connected RES plants increase partially the loadability margin. The sensitivity analysis performed shows that the MV plants may provide additional reactive support to the high voltage grid, but their impact is minimal compared to the reactive contribution of the HV connected plants.

6.3 2050 Network

The 2050 dispatching profiles described in chapter 3 have been analysed as well. As for 2030, first, the base case results are analysed, where only the synchronous machines provide the reactive support. Again, these preliminary results are not realistic: they are used as a first insight and benchmark for the subsequent assessment. Then, a second study has been performed considering the reactive contribution given by the RES and BESS [23] as well. The analysis has been stopped as soon as the voltage profile of one single HV busbar goes below the lower 0.9 limit. The 2050 dispatching profiles present a lower percentage of synchronous machines compared to 2030: a higher voltage instability is hence expected.

6.3.1 Base case

6.3.1.1 High Export dispatching profile

The voltage profiles of the 400 kV busbars of the *High Export* dispatching profile are shown in Figure 186, starting from the initial demand of 1835 MW; the maximum demand achievable is equal to 3565 MW, when several nodes go below the 0.9 limit.

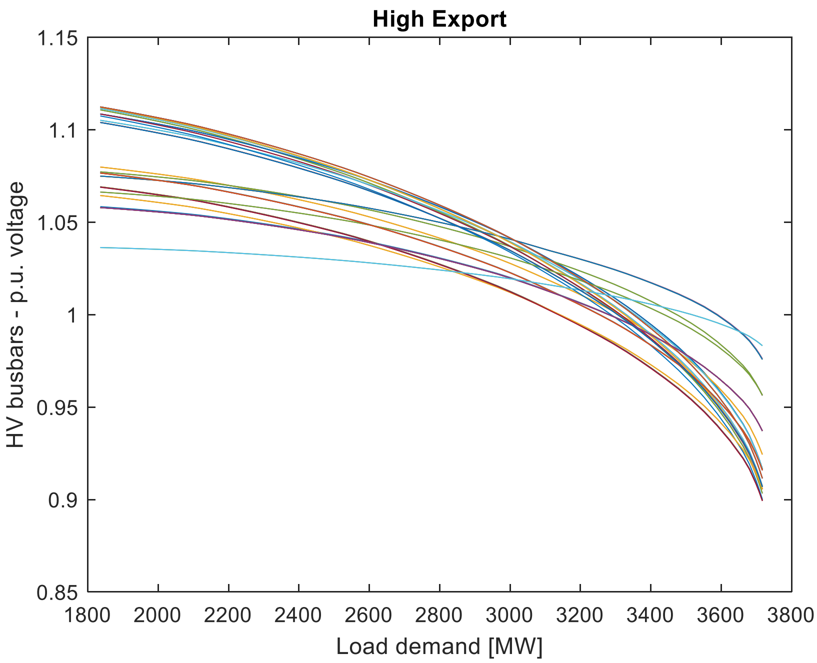

Figure 186. HV voltage profile of the High Export dispatching profile.

6.3.1.2 High Import dispatching profile

The voltage profiles of the 400 kV busbars of the *High Import* dispatching profile are shown in Figure 187, starting from the initial demand of 3220 MW; the maximum demand achievable is equal to 3596 MW.

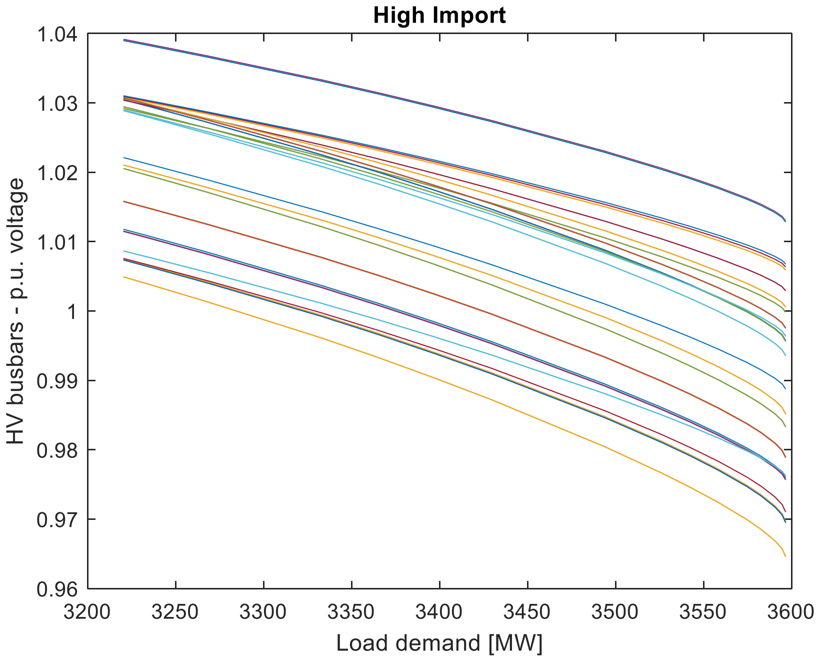

Figure 187. HV voltage profile of the High Import dispatching profile.

6.3.1.3 High Load dispatching profile

The voltage profiles of the 400 kV busbars of the *High Load* dispatching profile are shown in Figure 188, starting from the initial demand of 4088 MW; the maximum demand achievable is equal to 5498 MW, when one node (orange line) goes below the 0.9 limit.

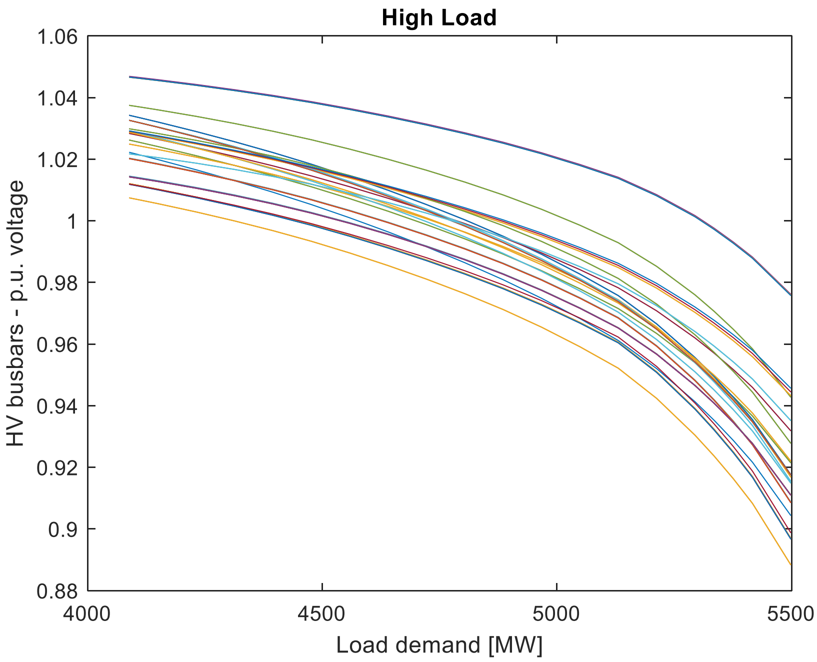

Figure 188. HV voltage profile of the High Load dispatching profile.

6.3.1.4 Low Load dispatching profile

The voltage profiles of the 400 kV busbars of the *Low Load* dispatching profile are shown in Figure 189, starting from the initial demand of 1510 MW; the maximum demand achievable is equal to 3346 MW.

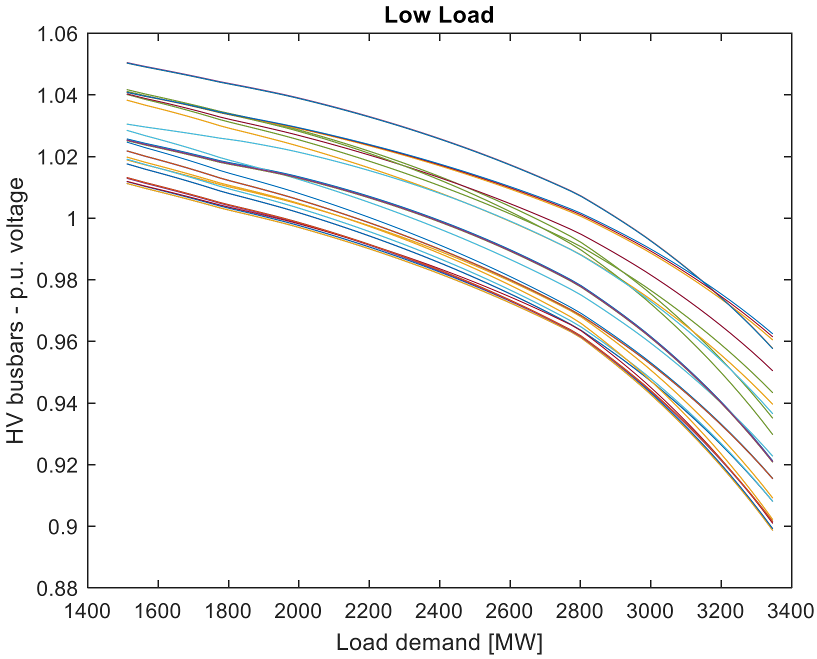

Figure 189. HV voltage profile of the Low Load dispatching profile.

6.3.1.5 Island dispatching profile

The voltage profiles of the 400 kV busbars of the *Island* dispatching profile are shown in Figure 190, starting from the initial demand of 4289 MW; the maximum demand achievable is equal to 4857 MW.

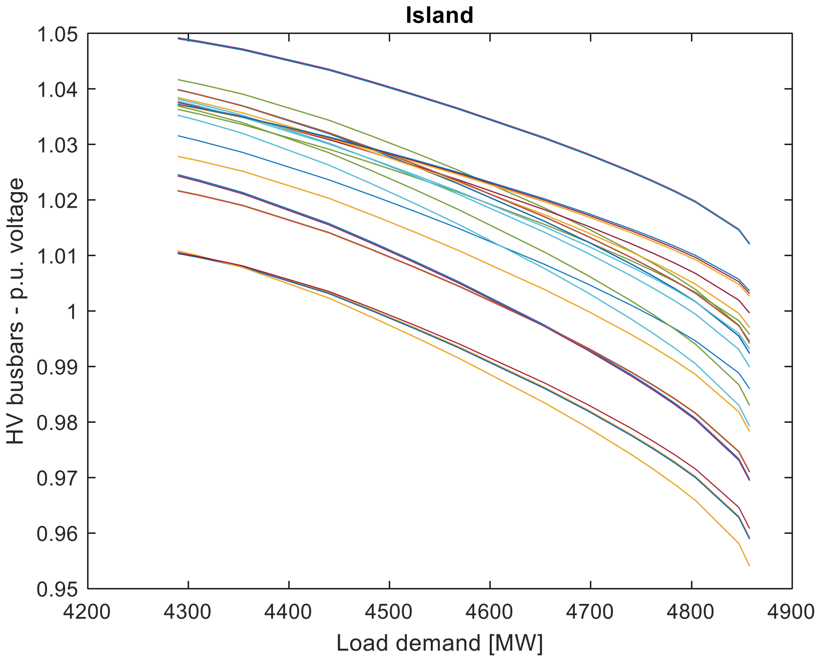

Figure 190. HV voltage profile of the Island dispatching profile.

6.3.1.6 Lines out of service dispatching profile

The voltage profiles of the 400 kV busbars of the *Line out of service* dispatching profile are shown in Figure 191, starting from the initial demand of 1510 MW; the maximum demand achievable is equal to 3225 MW, then various nodes go below the 0.9 limit.

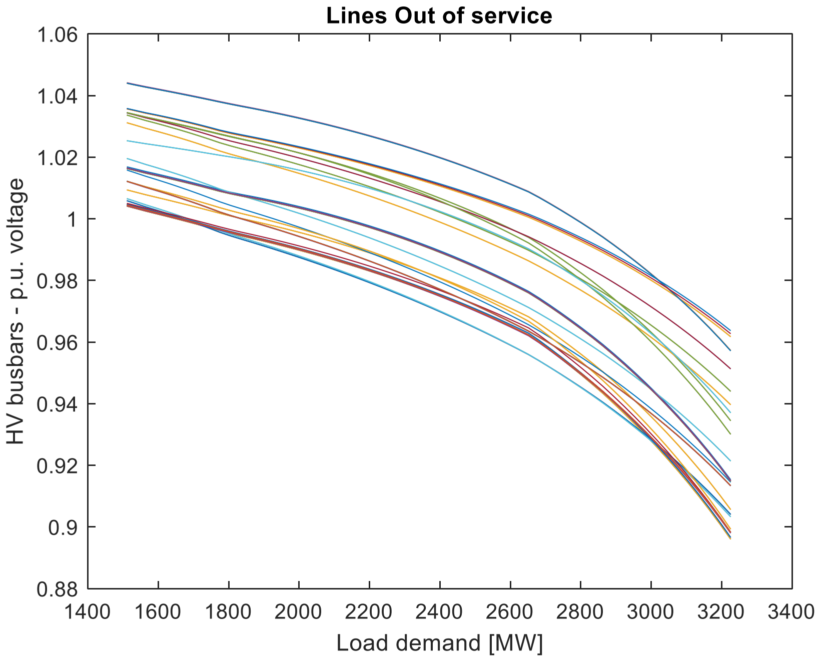

Figure 191. HV voltage profile of the dispatching profile with the 230 kV Lines out of service.

6.3.1.7 Summary

The 2050 results are finally summarized in Table 52 (the critical dispatching profiles are highlighted in bold), along with the loadability margin in MW and percentage. It can be easily appreciated that **the *High Import* and *Island* profiles present the lowest loadability margins**, less than 15 % and, along with loadability of the *High Load* one, they are much lower than the adopted threshold of 40 %: additional resources must be here employed to increase voltage stability margins, since the synchronous machines only are not enough to guarantee a satisfactory stability level. The remaining dispatching profiles already present enough loadability.

Dispatching profile	Initial Load [MW]	Final Load [MW]	Loadability [MW]	Loadability [%]
High Export	1835	3717	1882	102.5
High Import	3220	3596	376	**11.7**
High Load	4088	5498	1410	34.5
Low Load	1510	3346	1836	121.5
Island	4289	4857	568	**13.2**
Lines out of service	1510	3225	1715	113.5

Table 52. Loadability margins for the selected dispatching profiles for 2050.

6.3.2 RES contribution

The reactive contribution of the RES has been considered in the voltage stability analysis. All the HV connected wind plants, the photovoltaic plants connected to the HV and MV network, representing the MV dispersed generation, and the BESS have been modified to allow them to provide reactive power support. All the inverters have been set up with the current Italian standards as described in Section 6.1. Since a low level of loadability have been detected, to maximise the reactive support, the analysis has been carried out with no restrictions for the inverters: they can provide their full capability and hence overreaching the existing limits given by Terna in [21][22][23].

The results are shown in Table 53. **This solution**, with “full inverters capability”, **offers quite satisfactory results compared to the base case**, as in all the dispatching profiles the margin is increased. Despite this, in the *High Import* and *Island* ones, the loadability is still too low and hence cannot be considered acceptable, even if it is almost doubled compared to the base case. The *High load* profile reached instead an acceptable margin.

Dispatching profile	Final Load [MW]	Loadability [MW]	Loadability [%]	Loadability without RES [%]
High Export	4592	2757	150.2	102.5
High Import	3993	773	**24.0**	**11.7**
High Load	5702	1614	40.0	34.5
Low Load	4887	3376	223.5	121.5
Island	5791	1502	**35.0**	**13.2**
Lines out of service	4615	3105	205.5	113.5

Table 53. Loadability margins for the selected dispatching profiles for 2050 with the full RES reactive contribution.

Table 54 and Table 55 show respectively the loadability margin assuming a medium inverter capability for the RES plants, limited at the 65 % of the active power, and the one currently imposed by Terna, limited at the 35 %: the loadability margins are significantly lower, especially for the dispatching profiles highlighted in bold. The proposed approach to extend the capability for all the RES plants represents a potential solution, but in some hourly profiles the grid still requires additional reactive resources. The MV plants have been always assumed capable to provide full reactive contribution, as shown for 2030, the reactive demand required by the MV feeders can be neglected at the HV level.

Dispatching profile	Initial Load [MW]	Final Load [MW]	Loadability [MW]	Loadability [%]
High Export	1835	4585	2750	149.7
High Import	3220	3920	700	**21.75**
High Load	4088	5702	1614	40.0
Low Load	1510	4797	3287	217.5
Island	4289	5677	1388	**32.35**
Lines out of service	1510	4555	3044	201.5

Table 54. Loadability margins for the selected dispatching profiles for 2050 with a medium RES reactive contribution.

Dispatching profile	Initial Load [MW]	Final Load [MW]	Loadability [MW]	Loadability [%]
High Export	1835	4562	2727	148.6
High Import	3220	3837	617	**19.1**
High Load	4088	5702	4088	40.0
Low Load	1510	4645	3135	207.5
Island	4289	5457	1168	**27.2**
Lines out of service	1510	4404	2894	191.5

Table 55. Loadability margins for the selected dispatching profiles for 2050 with a low RES reactive contribution.

6.3.3 Critical dispatching profiles

Analysing the results, in both the *High Import* and *Island* dispatching profiles, the "critical busses" are two HV nodes close to Priolo, where two large thermal plants are nowadays connected, but are considered decommissioned in 2050: Erg Nuce Nord and Priolo Gargallo. For the *High Import* profile, the critical node is the PRGP busbar while for the *Island* one the EGNP busbar, both connected to the HV 150 kV substation of Melilli, which is the interconnection with the 230 and 400 kV lines.

According to this, the synchronous machines of the Priolo power plants (four machines of the Erg Nuce Nord and two for the Priolo Gargallo (PRGP)) have been assumed as still in operation as synchronous condensers only, to guarantee a suitable reactive support. This solution is cheap, reasonable, and already acceptable nowadays, since Terna is managing to install synchronous condensers in a few old thermal plants in south of Italy to provide inertia and voltage control to stabilize the grid.

Assuming the full reactive capability of the RES converters and thanks to the Priolo compensators, the loadability can be increased for the *Island* profile up to 40 % (Figure 192):

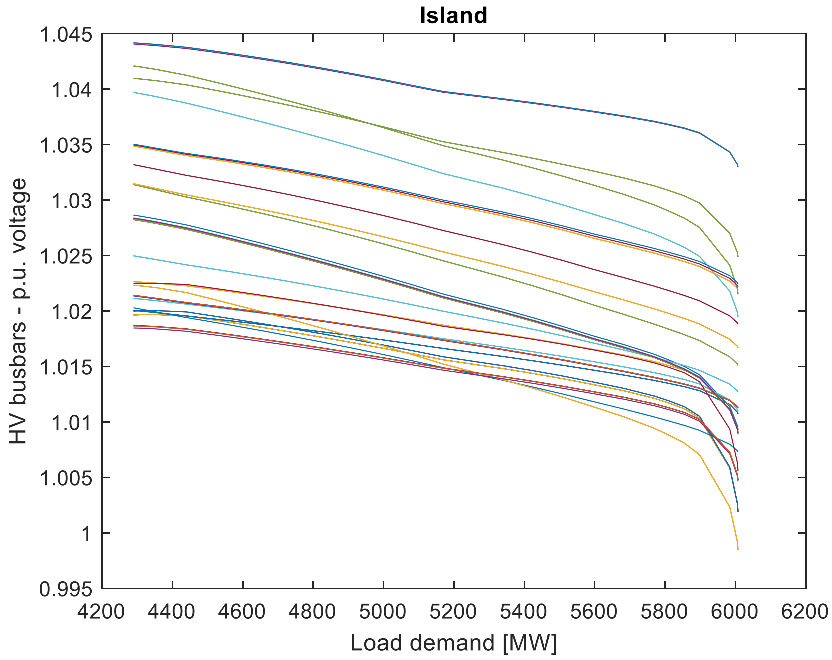

Figure 192. HV voltage profile of the Island dispatching profile.

and for the *High Import* dispatching profile up to 60% (Figure 193):

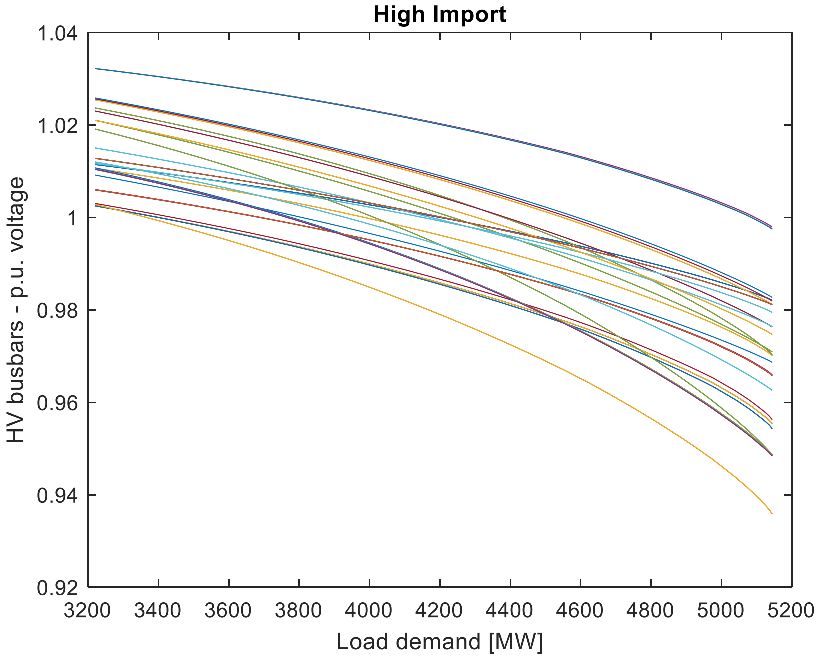

Figure 193. HV voltage profile of the High Import dispatching profile.

The results are summarized in the following table (Table 56, where the improvements are highlighted): for all the other dispatching profiles, the Priolo compensators can be kept off, as they already present a reasonable loadability margins.

Dispatching profile	Final Load [MW]	Loadability [MW]	Loadability [%]	Loadability without Priolo [%]
High Export	4592	2757	150.2	150.2
High Import	5144	1924	**60.0**	**24.0**
High Load	5702	1614	40.0	40.0
Low Load	4887	3376	223.5	223.5
Island	6007	1718	**40.0**	**35.0**
Lines out of service	4615	3105	205.5	205.5

Table 56. Loadability margins for the selected dispatching profiles for 2050 with a full RES reactive contribution and Priolo as synchronous compensator.

To better investigate the problem, a second analysis has been carried out, where the power plants in Priolo have been completely dismantled and the connection busses employed for the connection of wind turbine parks, hence taking advantage of the already existing infrastructures. The new wind turbines have been connected to the grid through PWM converters, able to provide reactive power. To maximise the reactive support, the capability has again been extended up to the maximum available (previously defined as “full inverters capability”) and the loadability margins have been recalculated: results are shown in Table 57.

Dispatching profile	Final Load [MW]	Loadability [MW]	Loadability [%]	Loadability without Priolo [%]
High Export	4592	2757	150.2	150.2
High Import	5625	2405	**74.6**	**24.0**
High Load	5702	1614	40.0	40.0
Low Load	4887	3376	223.5	223.5
Island	6036	1747	**41.0**	**35.0**
Lines out of service	4615	3105	205.5	205.5

Table 57. Loadability margins for the selected dispatching profiles for 2050 with a full RES reactive contribution of Priolo as wind park.

Thanks to the larger reactive capability provided by the converters, the *High Import* dispatching profile can reach a satisfactory loadability level equal to 75 %, while in the *Island* one is increased by few MW up to a final 41 %; anyway, this latest value can be considered suitable for the grid stability and the analysis can be now considered settled.

6.3.4 2050 Conclusions

The voltage stability of the power system of Sicily, forecasted for the year 2050, has been here analysed in the six different dispatching profiles identified:

1. High Export;
2. High Import;
3. High Load;
4. Island;
5. Low Load;
6. Lines out of service.

As for 2030, in each dispatching profile, the voltage stability of Sicily has been analysed; in particular, the critical point of voltage instability has been found increasing the active power demand of the loads until the power flow calculation no longer converges or some HV nodes go below the under voltage limit of 0.9 p.u.

According to the latest Terna requirements, renewable energy sources connected to the grid through electronic converters have been equipped with a suitable capability curve in order to provide reactive support. Simulations have been first performed considering only the synchronous generators reactive contribution and then the RES support as well. Since the 2050 dispatching profiles present a lower percentage of synchronous machines compared to 2030, **a higher voltage instability has been observed, unless flexibility provided by RES is considered**.

It has been noticed that when Sicily is importing power from continental Italy, it is facing a high-power demand or it is even not connected, its loadability margin, and hence its voltage stability, is reduced. To support voltage in such conditions, the capability of the static converters has been extended up to the maximum available, supporting the voltage stability to a satisfactory level. For the *Island* and *High Import* dispatching profiles the local reactive compensation at the Priolo substation allows to increase the loadability margin.

As a general conclusion for 2050:

- Sicily does not present a good loadability margin in the base case, with both the combination of synchronous generators and RES plants equipped with the current reactive settings [21][22];
- However, the presence of RES plant with “full inverters capability”, along with **specific compensation in local substations, improves the voltage stability and guarantees the voltage security of the power system**.

7 Conclusions

This report summarizes the results of the dynamic analysis carried out by ENSiEL for WP1 of the OSMOSE project (T1.4.3), concerning the feasibility of the scenarios and dispatching profiles identified by T1.2 and T1.3 for 2030 and 2050.

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. These simulations were performed on a dedicated large grid model of the electrical network, i.e., the Sicilian network, provided by Terna, the Italian Transmission System Operator. This grid model was updated according to both the capacities defined by the scenarios provided by Task 1.1 and the system-wide balancing of energy supply and demand identified area by area by Task 1.2. Therefore, T1.4.3 has evaluated if the outputs of the above-mentioned tasks are feasible from a dynamic point of view, identified possible lack of stability and, in such a case, suggested possible countermeasures, picking up any flexibility resource that can be useful.

7.1 2030 Network

Concerning the **large perturbation angle stability**, in all the cases where the connection with continental Italy is kept, even if with one or two out of the three cables available, frequency does not go outside normal operating conditions which, according to the current Italian grid code [19], is defined by the range 49.9 Hz – 50.1 Hz. This occurs both with and without the flexibility option provided by wind generators (synthetic inertia (SI)). However, in general, SI allows the maximum frequency deviation and frequency derivative to be reduced. Such effect results to be relatively small when the connection with continental Italy is in operation, and the overall system inertia is huge, if compared with the portion provided by the wind generators installed in Sicily.

In the *Island* profile, the loss of the inertia and of the primary regulation coming from continental Italy makes the frequency generally less stable. With one of the two simulated generation loss events, frequency exits from the normal operating conditions (which in the islanded case is defined by the range 49.5 Hz – 50.5 Hz [19]) and **stability can be only guaranteed by the provision of flexibility from the modulation of flexible loads** (DSR), with no load shedding.

A second critical situation (though much less probable) has been detected in the *High Import* profile. Here, the outage of two of the three connections with continental Italy, because of the high level of import, causes the outage of the third line and, consequently the islanding of Sicily, with the loss of 1100 MW of power import. The provision of flexibility from the modulation of loads (DSR) has been tested in this case. DSR has resulted to be useful to reduce the frequency derivative and the maximal frequency deviation.

Regarding the stability of the system to **small perturbations**, it has been found that the system does not present major stability issues, except the *High Export* dispatching profile, presenting a not properly damped oscillatory mode. However, its **stability can be improved thanks to**

the synthetic inertia contribution provided by wind farms and by tuning the relevant PSSs. All the other dispatching profiles do not show poorly damped oscillation modes.
Additional studies confirmed that **the stability of poorly damped modes improves introducing the contribution of synthetic inertia and by tuning the PSS gain of the relevant generators**.

Voltage instability has been studied by increasing the active power demand of the loads until the load flow calculation no longer converges or some HV nodes go below the undervoltage limit of 0.9 p.u. Simulations have been firstly performed considering only the synchronous generators reactive contribution and then with the RES support as well. **It has been noticed that when Sicily is importing power from continental Italy or its load demand is high**, its loadability margin, and hence its voltage stability**, is reduced**. However, **the reactive support of the renewable energy sources contributes to increase the overall loadability margin** in all the dispatching profiles.

In 58 the main conclusions and solutions of the selected dispatching profiles are shown:

Type of stability	Is stability guaranteed without flexibility options?	Does the operational condition need specific flexibility options?	Solutions identified / Notes
High Export			
Large perturbation angle stability	YES	NO	Synthetic inertia stabilizes the grid
Small perturbation angle stability	NO	YES	FCWT synthetic inertia and PSS tuning
Voltage stability	YES	NO	-
High Import			
Large perturbation angle stability	YES	YES	DSR FCR may be required in case of stressful, but almost unlikely, events
Small perturbation angle stability	YES	YES	FCWT synthetic inertia and PSS tuning
Voltage stability	YES	YES	Reactive contribution from RES plants is paramount
High Load / Low Gas			
Large perturbation angle stability	YES	NO	-
Small perturbation angle stability	YES	NO	-
Voltage stability	YES	NO	-
Island			
Large perturbation angle stability	NO	YES	DSR FCR is required
Small perturbation angle stability	YES	NO	-
Voltage stability	YES	YES	Reactive contribution from RES plants is paramount
Low Load / Low Gas			
Large perturbation angle stability	YES	NO	
Small perturbation angle stability	YES	NO	-
Voltage stability	YES	NO	-
Lines out of service			
Large perturbation angle stability	YES	NO	
Small perturbation angle stability	YES	NO	-
Voltage stability	YES	NO	-

Table 58. 2030 conclusions.

7.2 2050 Network

Concerning 2050 operating conditions studied, **large-perturbation angle stability** is guaranteed in all the dispatching profiles and for all events, except for a very unlikely operating condition that results in a *High Import* power loss. However, it is possible to get **stability in such a critical operating condition, taking into account the contribution of BESSs and/or DSR, which results to be mandatory**.

As for the post fault steady state, **the contribution to frequency regulation of BESSs and/or DSR is generally sufficient to keep frequency in the range 49.9 Hz – 50.1 Hz. In only two cases this has resulted not possible; however, this constraint can be managed by subsequent control actions.**

Regarding the **small-perturbation angle stability**, for the dispatching profiles in which RES support frequency control is not active, in some cases low damped electromechanical modes are present, in particular an inter-area mode. Like for 2030, it has been shown how it **can be stabilized thanks to the contribution of synthetic inertia provided by BESS and wind farms and by tuning the PSSs of the relevant generators**.
As in the 2030 network, also in 2050 the Sicilian grid shows strong small perturbation stability features. Furthermore, compared to the 2030 network, **the grid shows a larger variety of flexibility options available to tackle frequency instabilities.**

Finally, simulations assessing the **voltage stability** have been firstly performed considering only the synchronous generators reactive contribution and then the RES support as well. Since the 2050 presents a lower percentage of synchronous machines compared to 2030, **a higher voltage instability has been observed, unless flexibility provided by RES is considered**. That flexibility has proved to be able to manage all operating conditions studied.

In Table 59 the main conclusions and solutions of the selected dispatching profiles are shown:

Type of stability	Is stability guaranteed without flexibility options?	Does the operational condition need specific flexibility options?	Solutions identified / Notes
High Export			
Large perturbation angle stability	YES	YES	DSR and BESS FCR are required to guarantee the normal operating conditions
Small perturbation angle stability	YES	NO	-
Voltage stability	YES	YES	Extend the reactive capability of RES units
High Import			
Large perturbation angle stability	NO	YES	DSR and BESS FCR are required
Small perturbation angle stability	YES	YES	Synthetic inertia provided by FCWT and BESS, and PSS tuning
Voltage stability	NO	YES	Extend the reactive capability of RES units + Local compensation in Priolo substation
High Load			
Large perturbation angle stability	YES	NO	-
Small perturbation angle stability	YES	NO	-
Voltage stability	NO	YES	Extend the reactive capability of RES units
Island			
Large perturbation angle stability	NO	YES	DSR and BESS FCR are required
Small perturbation angle stability	YES	NO	-
Voltage stability	NO	YES	Extend the reactive capability of RES units + Local compensation in Priolo substation
Low Load			
Large perturbation angle stability	NO	YES	DSR and BESS FCR are required
Small perturbation angle stability	NO	YES	Synthetic inertia provided by FCWT and BESS, and PSS tuning
Voltage stability	YES	YES	Extend the reactive capability of RES units
Lines out of service			
Large perturbation angle stability	NO	YES	DSR and BESS FCR are required
Small perturbation angle stability	NO	YES	Synthetic inertia provided by FCWT and BESS, and PSS tuning
Voltage stability	YES	YES	Extend the reactive capability of RES units

Table 59. 2050 conclusions.

8 Bibliography

[1] J. Weibezahn, L. Göke, D. Poli, V. Protard, Y. Bourien, G. Ažman, N. Grisey, "*Flexibility cost and operation data outlook. D.1.2*", May 17, 2019.

[2] J. Weibezahn, L. Göke, L. Orrù, N. Grisey, "*European Long-Term Scenarios Description. D.1.1*", May 17, 2019.

[3] J. Bourmaud, N. Grisey, "*T.1.2 - Optimal Mix of Flexibility. Internal document. Description of the E-highway 2030 grid clustering*". January 31, 2020.

[4] D. Macalli, R. Zaottini, V. Ilea, G. Giannuzzi and A. Berizzi, "*The role of load models and reactive power support during large frequency transients",* 2016 51st International Universities Power Engineering Conference (UPEC), Coimbra, 2016, pp. 1-6. doi: 10.1109/UPEC.2016.8114131.

[5] P. Kundur, *Power System Stability and Control*. New York: McGraw-Hill, 1994.

[6] Map of Sicily, 380 – 220 kV system, *http://www.regione.sicilia.it*

[7] Enel S.p.A. Impianto idroelettrico dell'Anapo. *http://www.*enel.it.

[8] Enel S.p.A. Centrale di Augusta. *http://www.*enel.it.

[9] G. Gatti and ERG Power & Gas, "Priolo Supersite". *http://www.erg.it*.

[10] E.ON. Centrale di Trapani. *http://www.eon-italia.com*.

[11] Eni S.p.A. Raffineria di Gela. *http://www.eni.com.*

[12] A2A Energiefuture S.p.A. Centrale di San Filippo del Mela. *http://www.energiefuture.eu.*

[13] Termica Milazzo S.r.l. Centrale termoelettrica di Milazzo. *http://www.termica-milazzo.it*.

[14] Enel S.p.A. Centrale di Termini Imerese. *http://www.enel.it*.

[15] Terna, Grid Code Annexes 11, "*Criteri Generali per la Taratura delle Protezione delle Reti a Tensione Uguale o Superiore a 110 kV*" (Italian only).

[16] ENSiEL, "*Stability Aspects*", WP1 - T1.4 Deliverable 2019.12.07.

[17] GAUDI' portal, *https://www.terna.it/it/sistema-elettrico/gaudi.*

[18] Terna, Grid Code Annexes 12, "*Criteri di Taratura dei Relè di Frequenza del Sistema Elettrico e Piano di Alleggerimento*" (Italian only).

[19] Terna, "*Codice di trasmissione, dispacciamento, sviluppo e sicurezza della rete*", April 2007.

[20] ENTSO-E, "*Frequency Stability Evaluation Criteria for the Synchronous Zone of Continental Europe: Requirements and impacting factors*", March 2016.

[21] Terna, Grid Code Annexes 17, Allegato 17 "*Centrali Eoliche – Condizioni generali di connessione alle reti AT. Sistemi di protezione, regolazione e controllo*" (Italian only).

[22] Terna, Grid Code Annexes 68, Allegato 68 "*Centrali Fotovoltaiche – Condizioni generali di connessione alle reti AT. Sistemi di protezione, regolazione e controllo*" (Italian only).

[23] CEI 0 - 16, "*Regola tecnica di riferimento per la connessione di Utenti attivi e passivi alle reti AT ed MT delle imprese distributrici di energia elettrica*" (Italian only).