European Network of
Transmission System Operators
for Electricity

SYSTEM DEFENCE PLAN

Draft | 26 January 2022

SPD – Inertia TF

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The goal of this report is to check the validity of the system defence plan of the Continental European synchronous area. For this purpose, different scenarios, consisting of a peak load, low load and peak RES scenario for 2022 and 2030 are analyzed.

For the analysis a single-busbar model, developed in TF Inertia of SPD, is applied, which models the frequency control mechanisms, such as primary control (FCR), LFSM, HVDCs, self-regulating effect of loads, interruptible loads and under-frequency load shedding, of the interconnected power systems during power imbalances. In addition, the model also takes into account the impact of non-conform disconnection of generation units based on the collected data for the Continental European synchronous area from 2021. The parameter which is observed is the system frequency, which represents, based on the model that has been used, the frequency of the 'center of inertia'.

In order to check the validity of the system defence plan also for non-standard contingencies, power imbalances up to 10 % of the total system load are analyzed, which exceed the dimensioning incident for primary control (FCR) of 3 GW of generation outages. This results in power imbalances of up to 44 GW depending on the specific scenario. Taking into account restrictions regarding frequency and RoCoF, the results show that the current system defence plan works well for power imbalances up to ± 5 % of the total system load, as long as the power system stays interconnected and the capacity of non-conform generation units do not exceed the collected values among RG CE TSOs.

The results show the validity of the current system defence plan today, but also for 2030 considering a moderate decline of the system's inertia. In addition, the importance of implemented measures, such as the automatic disconnection of interruptible loads, disconnection of pump storages in pumping mode and activation of LFSM-O, becomes clear. These measures will become even more important in the future, due to a declining inertia of the power system.

Although the results show a validity of the current system defence plan for non-standard contingencies exceeding (3 GW of generation outages and 2 GW of load outages), system splits are out of scope of this report. A system split would pose a more severe challenge to the system resulting in even higher imbalances relative to the size as well as lower inertia and less available reserves and measures of the system defence plan. This might be the subject of future studies in this context.

Introduction and aim of the Document

Power system operation is based on principles and approaches which ensure a very high level of security of supply.

System frequency is one of the main measurands which reflect the quality of supply or with other words how “healthy” and secure the system is.

Fast control reserves are available within a range of +/- 200 mHz around the setpoint frequency of 50 Hz. Therefore, it can be assumed that, under the circumstances for which it was designed, the system is under control with sufficient reserve margins in this range.

If the frequency drops out of this range, additional actions for stabilising the power system balance are required. For this, system protection schemes or defence plans are setup to prevent or mitigate further frequency degradation and possible subsequent blackout of the system.

In over-frequency, generation units must reduce their output or, in any case, be stable at reference power; the only exception is the controlled staggered disconnection that ensures a stepwise equivalent reduction of injected power. On the other hand, in under-frequency, different countermeasures are adopted:

- Interruptible customers tripping (below 49.8 Hz)
- Hydro storage tripping (below 49.8 Hz)
- Load shedding (below 49 Hz)

All these countermeasures must be “fast” enough to be effective in counteracting the frequency decrease. This means that the typical intervention time is in the range of milliseconds and thus coherent with the rate of change of frequency in the emergency range. Therefore, this kind of action cannot be considered as reserve regulation behaviour, but purely as defence system action.

As frequency is a common and same value in the whole synchronous area, coordination of individual national defence plans is a must. The main principle is to ensure even distribution of several disconnection steps over the complete synchronous area to avoid dynamic phenomena which might trigger further disconnections and instability of the system.

The dynamic model calculations in the present report are based on the latest available defence plan settings which SPD SG acquired from all CE TSOs in two rounds of data collection questionnaires[1] in 2020 and 2021.

---

[1] *These questionnaires contain data for frequency thresholds and installed power of pump storages, interruptible loads and non-conform generation units.*

Non-conform generation disconnection

This chapter details the model input parameters concerning *Non-conform generation disconnection [2]*. These generation units disconnect between 50.2…51.5 Hz and 47.5…49.8 Hz. This, for example, includes units connected according to the REE (P.O.16) grid code (Spain), as they are allowed to disconnect after 3 seconds already at 48 Hz.

On the other side, *network code conform* generation are generation units that stay connected within the total frequency range of 47.5 … 51.5 Hz, as also required by the NC RfG.

As *non-conform generation disconnection* can have a large impact on the system behaviour, a detailed knowledge about distribution, parameters, and capacity of the related generation is of utmost importance. To accurately represent the behaviour of these units in the simulations performed in this report, a survey amongst all RG CE TSOs has been conducted.

The results of the survey can be seen in Table 1 and Table 2.

Table 1: Generation Disconnection at Over-Frequency

Frequency of Generation Disconnection (Hz)	Amount of Generation Disconnection (MW)
51.4	4 205
51.3	4 045
51.2	4 062
51.1	4 478
51.0	54 796
50.9	12 883
50.8	10 594
50.7	9 646
50.6	8 661
50.5	13 010
50.4	5 382
50.3	7 039
50.2	10 835

Table 2: Generation Disconnection at Under-Frequency

Frequency of Generation Disconnection (Hz)	Amount of Generation Disconnection (MW)
49.8	2 039
49.7	867
49.5	11 465
49.0	4 776
48.5	1 014
48.0	45 244

Table 1 and Table 2 show that the total amount of *non-conform generation disconnection* amounts to approx. 150 GW in the over-frequency regime between 50.2 and 51.4 Hz and approx. 19 GW in the under-frequency regime between 49.8 Hz and 49.0 Hz. During the simulation the frequency did not drop below 48.5 Hz and thus the related amounts of non-conform generation were not triggered.

Figure 1 details the pumps and interruptible loads (total amount in MW per each frequency threshold) that disconnect at frequency values below 50 Hz.

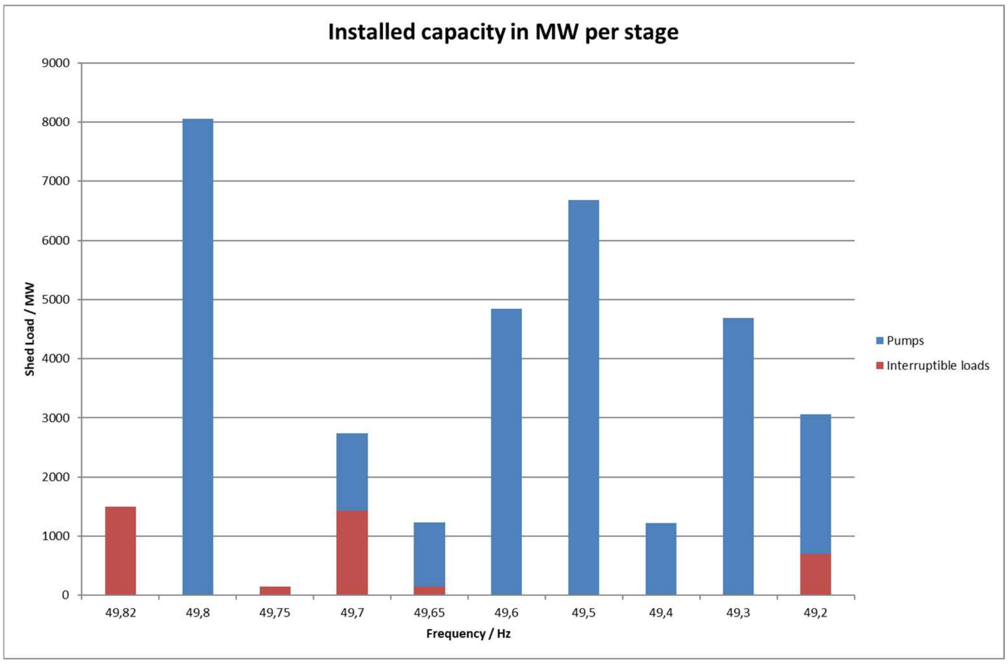

Figure 1 : Total amount per frequency threshold of interruptible loads and pumps

System Defence Plan: definition

Power Systems can be subjected to contingencies which in their severity exceed the values set at the defining the system design. These extreme contingencies are rare and often result from exceptional technical malfunctions, force majeure conditions or human errors. With respect to their causes and consequences, extreme contingencies are variegated and, therefore, not specifically considered in the design and planning policies of most utilities. Extreme or unforeseen contingencies can violate the admissible operational limits and bring the system in the emergency (disturbed) state in which it is not blacked out though, but it may not be able to fulfil its function with respect to consumer supply and power transits. Moreover, there is the risk of system collapse, mainly due to the loss of stability. Therefore, relevant actions must be taken immediately to bring back the system into acceptable conditions. In order to cope with and to minimize the impact of these rare but extreme contingencies, i.e. in particular to prevent a total system collapse, Defence Plans have been developed and implemented by all RG CE TSOs.

A System Defence Plan is a set of automatic or manual and fast acting schemes, which are designed to maintain system stability in case of severe contingencies that may trigger a cascading event that would bring the power system towards blackout state.

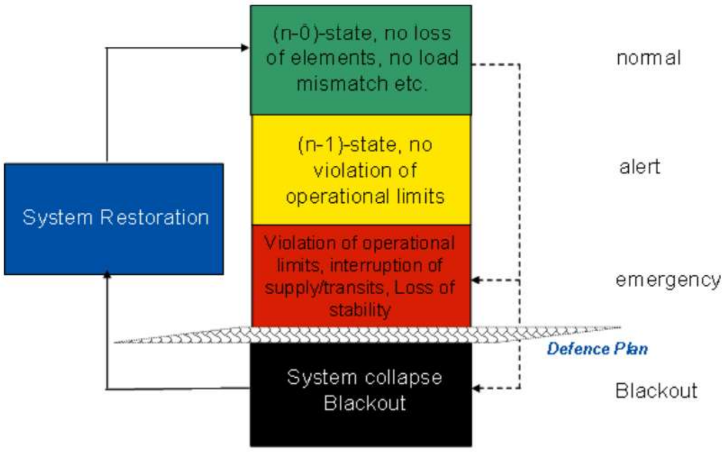

Figure 2 : System states definition (cf. GUIDELINES AND RULES FOR DEFENCE PLAN)

Defence Plans are a combination of Special Protection Schemes (SPS) that are usually centralized and designed for a limited set of triggering inputs, and other schemes that are rather distributed and designed to contribute to saving the system in multiple cases of possible extreme contingencies.

As every technical scheme, a Defence Plan is defined under specific boundary conditions and set of incidents, and it is subject to limitations. If the extreme contingency is too severe or happening in a degraded system condition, it may not be able to maintain the system stability. Nevertheless, System Defence Plans are defined in a robust way to be efficient in the most cases.

In case of severe frequency excursions, System Defence Plan schemes aim at re-establishing the balance of generation and load in a faster way than the automatic controls that are used during normal operation state.

Examples for schemes used during frequency excursions are under-frequency load (or pumping units) shedding, over-frequency generation shedding or controlled, fast adaption of the active power operating point of generation units (LFSM-O in over-frequency or LFSM-U in under-frequency). For HVDC links, specific control systems can be defined to support in case of extreme frequency excursions such as Emergency Power Control functions. All above mentioned schemes play a role in the context of the phenomena described in this report.

The mitigation actions for under-frequency reduce the system unbalance by increasing the generation, adapting the exchanges with non-synchronous areas and, as last resource, disconnection of loads.

It is worth underlining that defence systems and special protection schemes cannot guarantee success in every case. They only rather increase the probability to return the system into a stable state.

The following lists the elements of the system that are playing an impacting role during severe under-frequency events:

- Rotating masses Inertia
- Primary control (FCR)
- Secondary controller change control mode
- LFSM-U (Limited Frequency Sensitive Mode at Under-frequency)
- HVDC support from neighbouring synchronous system
- Emergency start-up of generating units (e.g. turbojets or gas turbines)
- Self-regulating effect of loads
- Hydro pump storage disconnection
- Interruptible loads shedding
- Automatic Under Frequency Load Shedding (UFLS) shedding
- BESS (Battery Energy Storage Systems)
- Manual load shedding

For the over-frequency, it is in the opposite way, but rather through reduction of generation, and minimizing the physical disconnection of generation, since generators should be always ready to restore their pre-fault condition:

- Rotating masses Inertia
- Primary control (FCR)
- LFSM-O (Limited Frequency Sensitive Mode at Over-frequency)
- HVDC support from neighbouring synchronous system
- Self-regulating effect of loads
- Over-frequency generation disconnection
- BESS (Battery Energy Storage Systems)

System Defence Plans are not limited to frequency aspects. Examples for System Defence Plan schemes for mitigating severe low voltages are blocking of transformer tap changers or under-voltage load shedding.

Other examples of coordinated SPS that could prevent severe frequency excursions or other instabilities (such as transient instability) are those designed to block, by fast reduction of flows, the cascading disconnection of lines/cables due to overloading. Such schemes, often deployed on system connected in antenna, detect the related risk and automatically shed load or generation.

Simulations

Simulation model

For analyzing the time-dependent behavior of the power system, an active power balance model, which has been developed and validated in previous studies [1], has been applied. The general structure of the model is shown in Figure 1.

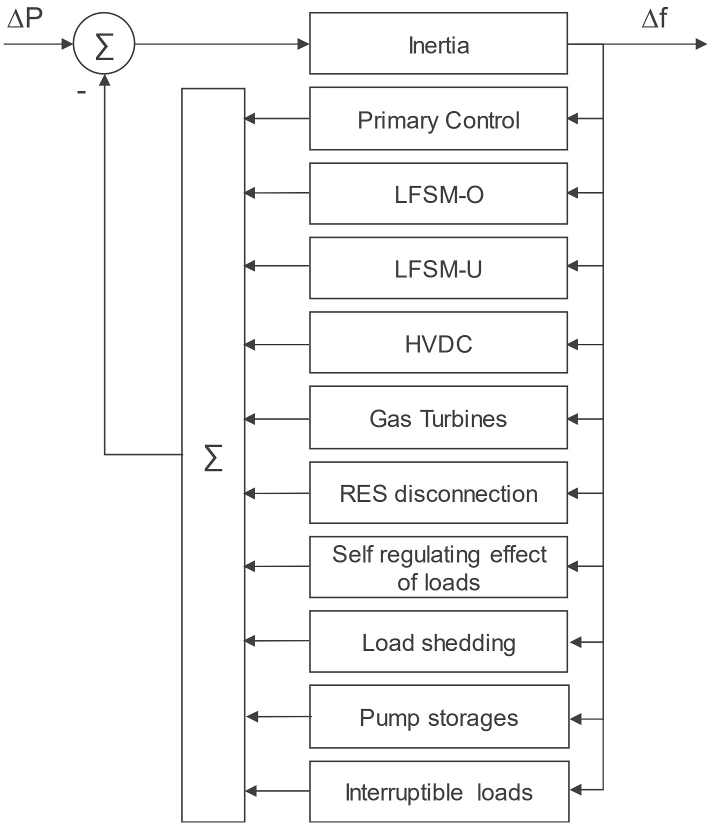

Figure 1: Schematic block diagram of reference model in Matlab/Simulink

The relevant frequency control mechanisms in the range of 47.5 Hz and 51.5 Hz having an impact on the frequency response are modelled and parametrized based on collected data in SPD SG. In this report, the non- conform disconnection of RES units is considered in the same frequency range by a total of 17 individual stages (see chapter “Non-conform generation disconnection”).

The results of the simulations are considered acceptable if no blackout occurs, i.e. if the 47.5 Hz and 51.5 Hz limits are not exceeded and the final steady-state frequency is close to 50 Hz.

Scenarios

This section presents the main scenarios and their underlying parameters, which are used for the simulations with the balance model. The main scenarios are derived from current observations (2021) based on ENTSO-E Transparency Platform data, dispersed generation data and the TYNDP 2020 scenario “National Trends” (NT2030).

Table 3 shows a comparison of six main scenarios. The scenarios in 2022 and 2030 are further categorized in three sub-scenarios which include peak load, low load, and peak RES scenario.

The chosen system conditions for each scenario were estimated from predicted time series data based on the same hours as in [1].

The main assumptions for the scenarios in 2030 are:

- Increase of system load (sector coupling, EVs, heating pumps, etc.)
- Decrease of network time constant T_{A} (increasing share of inverter-coupled generation)
- Slight change of pumping simultaneity factor (less pumping during low load; more pumping during high RES generation due to lower market prices).
- Decrease of the simultaneity factor for the infeed from non- conform RES (NC-RES) due to retrofitting and new RES installations

Table 3: Scenario Data

Year	Scenario	Load (GW)	PV (GW)	Wind (GW)	Gas (GW)	SRL (%/Hz)	Simultaneity factor pumps (%)	Simultaneity factor NC-RES (%)	T_{A} (s)
2022	Peak Load	435.0	8.5	72.0	58.0	2	0	40	6.5
	Low Load	200.0	6.5	19.5	11.0	2	45	10	7.0
	Peak RES	405.0	38.5	118.5	28.5	2	45	50	4.9
2030	Peak Load	450.0	25.0	90.0	80.0	2	0	30	6.0
	Low Load	200.0	10.0	40.0	10.0	2	40	5	6.0
	Peak RES	450.0	125.0	150.0	30.0	2	50	40	3.1

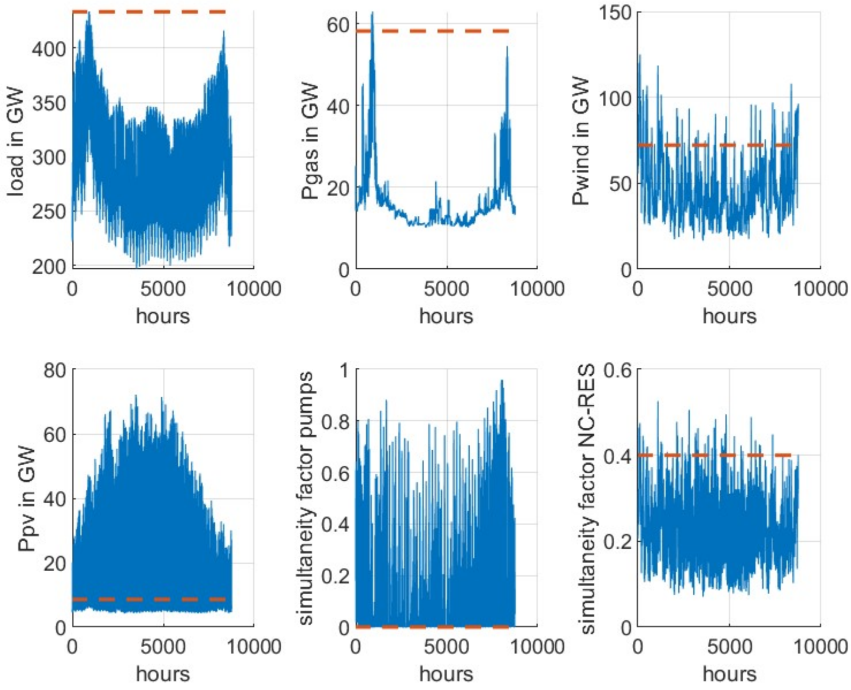

Figure 2 - High Load 2022

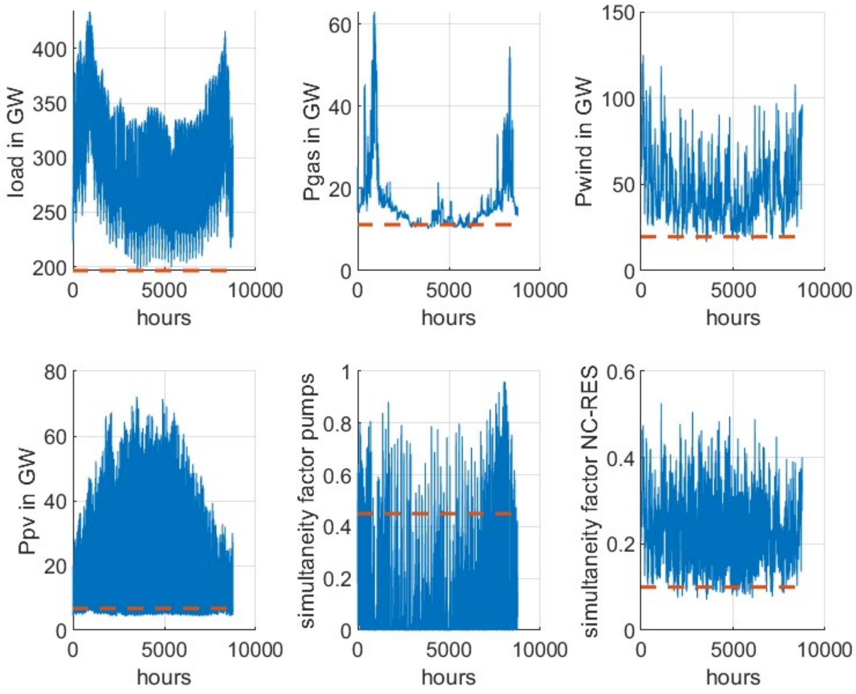

Figure 3 - Low Load 2022

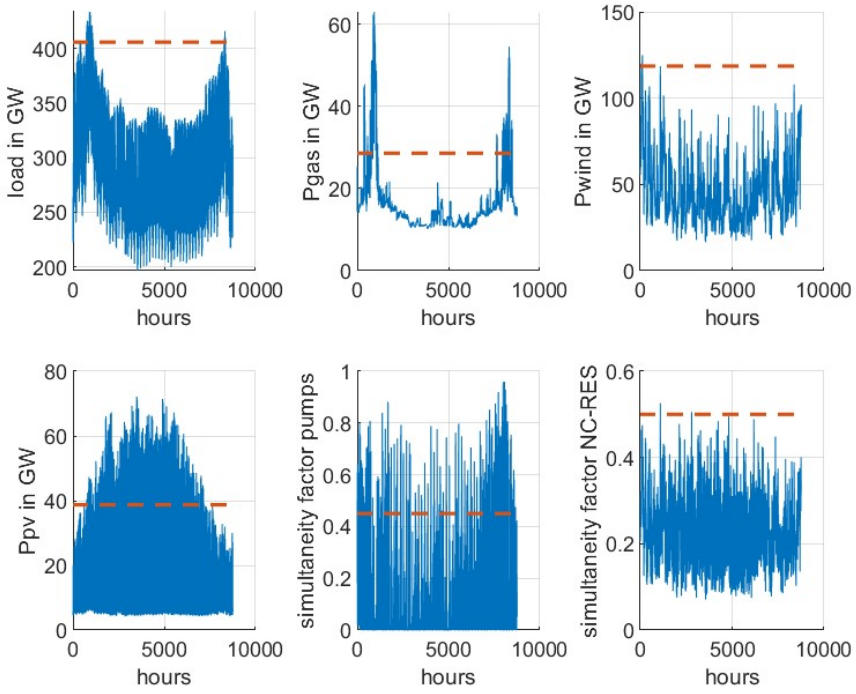

Figure 4 - High RES 2022

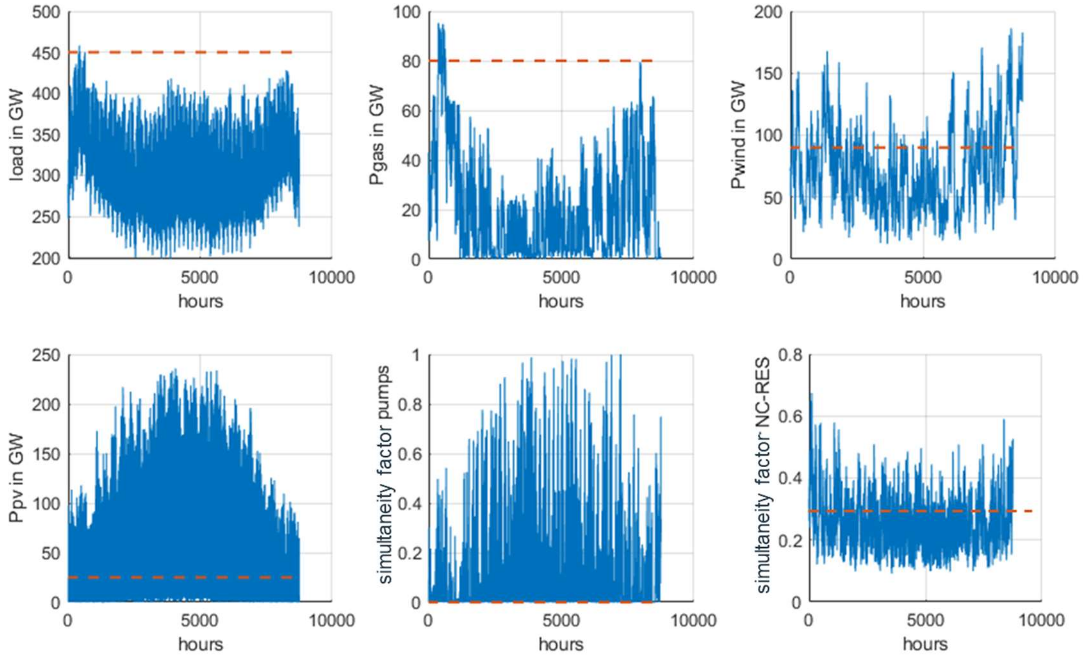

Figure 5 - High Load 2030

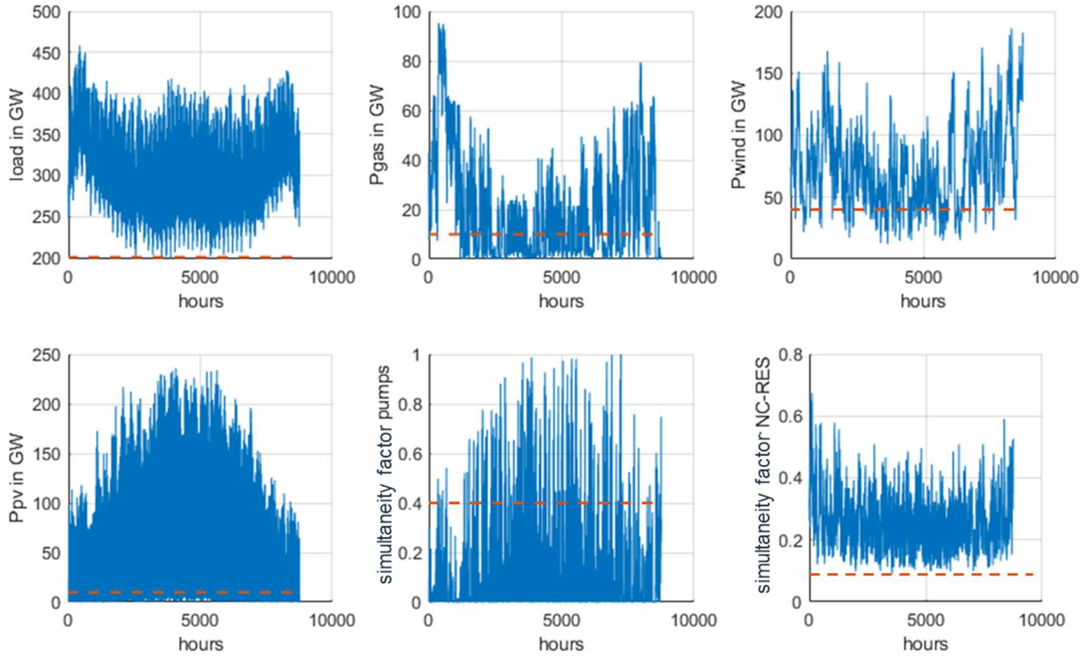

Figure 6 - Low Load 2030

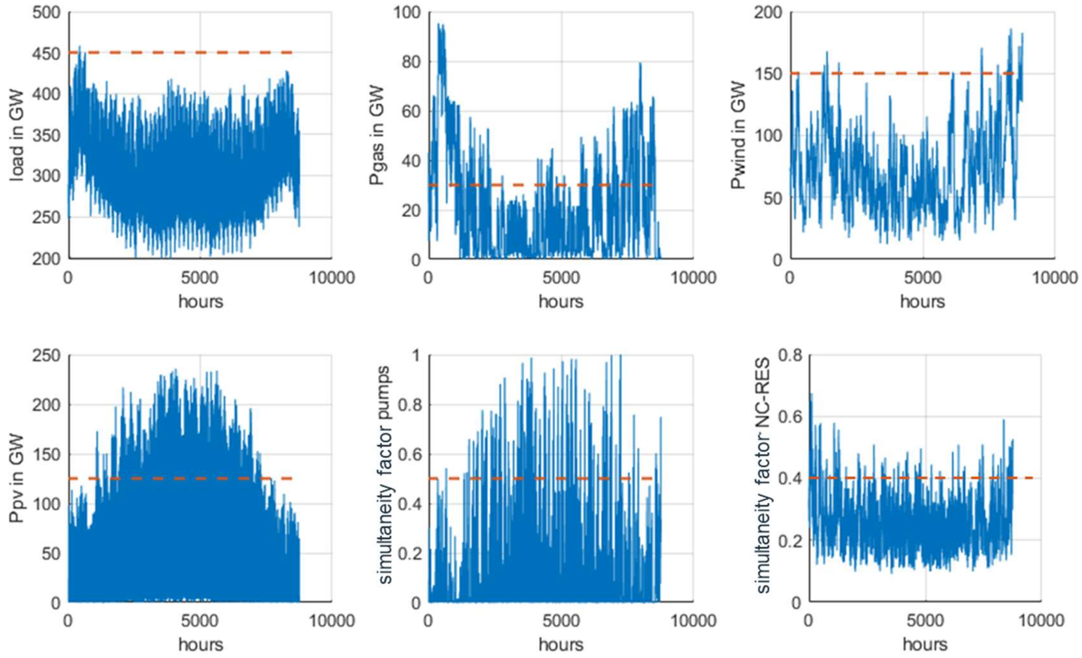

Figure 7 - High RES 2030

Simulation Results

In order to assess the current system defence plan, all six presented scenarios representing the years 2022 and 2030 (three by year) are applied to the active power balance model and the time dependent behavior of the system is analyzed. For this purpose, the applied load imbalance is varied in a range of -10 % to +10 %, representing either a loss of generation or load. For each simulation it is checked if the frequency can be kept within the limits of 47.5 Hz and 51.5 Hz with the help of the implemented measures of the system defence plan.

The results of the simulations are considered acceptable if no blackout occurs, i.e. if the 47.5 Hz and 51.5 Hz limits are not reached and not exceeded and if the final steady-state frequency is close to 50 Hz. In addition, the rate of change of frequency (RoCoF) must be maintained below 1 Hz/s, which is the maximum manageable RoCoF of current system protection schemes [1].

Check of system defence plan

Peak load scenarios

Figure 8 shows an evaluation of occurring maximum (fmax), minimum (fmin) and stationary end frequency (fstat) for the peak load scenarios for 2022 and 2030. It can be seen that for both scenarios the frequency is kept within the frequency limits of 47.5 Hz and 51.5 Hz for power imbalances in a range of ±10 %. However, due to the decreasing inertia of the system, the resulting frequency gradients increase in 2030 and load shedding is triggered at lower active power deficits. During active power surpluses this results in an increase of the occurring frequency maximums. In addition, a decay of the frequency after reaching 51.0 Hz can be observed, where interruptible loads are tripped to stabilize the frequency.

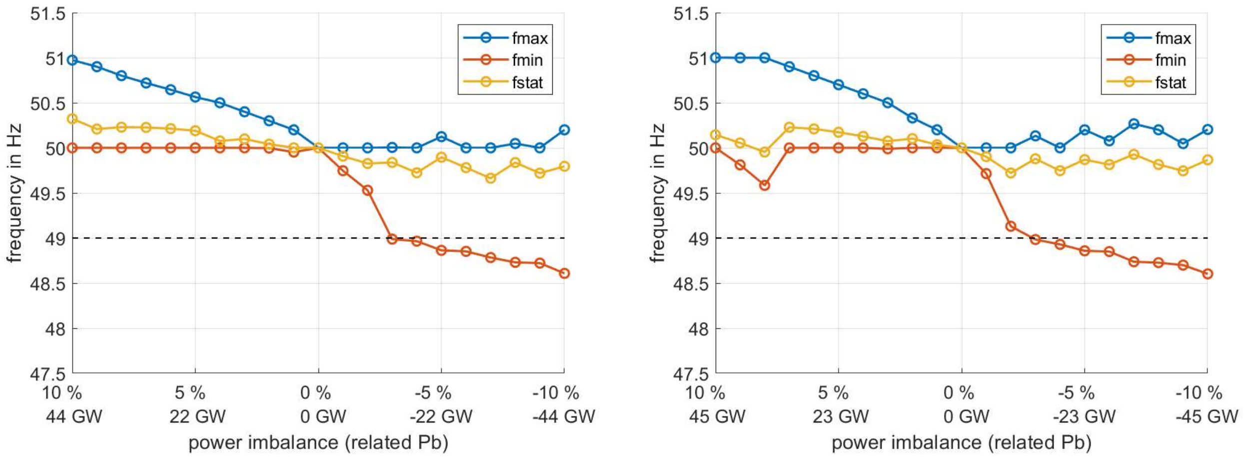

Figure 8: Results for peak load scenario 2022 (left) and 2030 (right)

Figure 9 shows the corresponding maximum rate of change of frequency (RoCoF) values during the simulation. Even for nonstandard contingencies with power imbalances exceeding 3 GW, the maximum RoCoF is below 1 Hz/s.

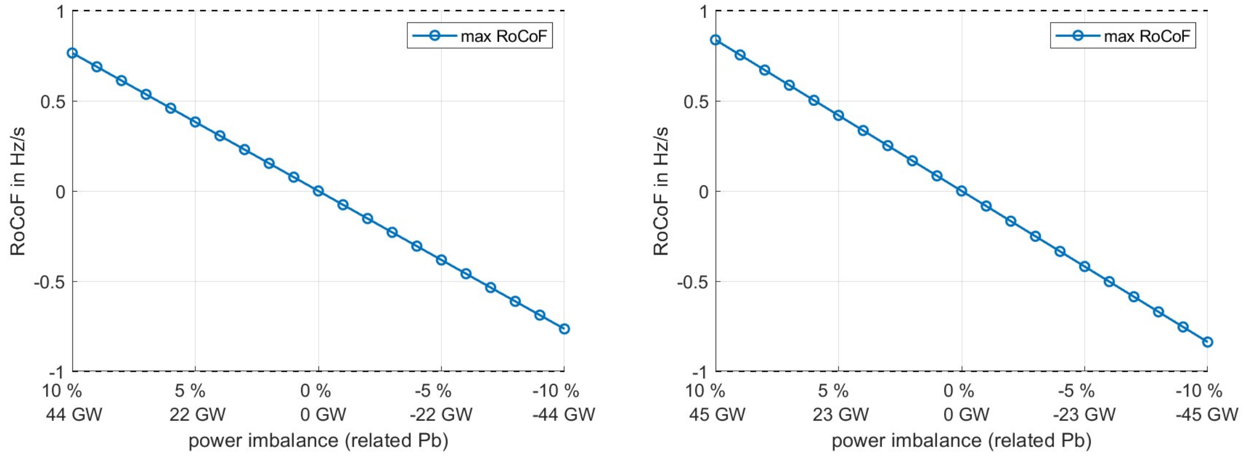

Figure 9: RoCoF values for peak load scenario 2022 (left) and 2030 (right)

In Figure 10, the individual contribution of the disconnection of pump storages in pumping mode (pump stor.), shedding of non-conform generation units (gen. shed.), under frequency load shedding (load shed.) and interruptible loads (inter. loads) towards balancing out the initial power imbalance are depicted. On the one hand, the disconnection of non-conform generation units helps stabilizing the frequency following power surpluses. On the other hand, the power deficits get even increased by disconnection of non-conform generation units, but compensated by interruptible loads, pump storages and load shedding.

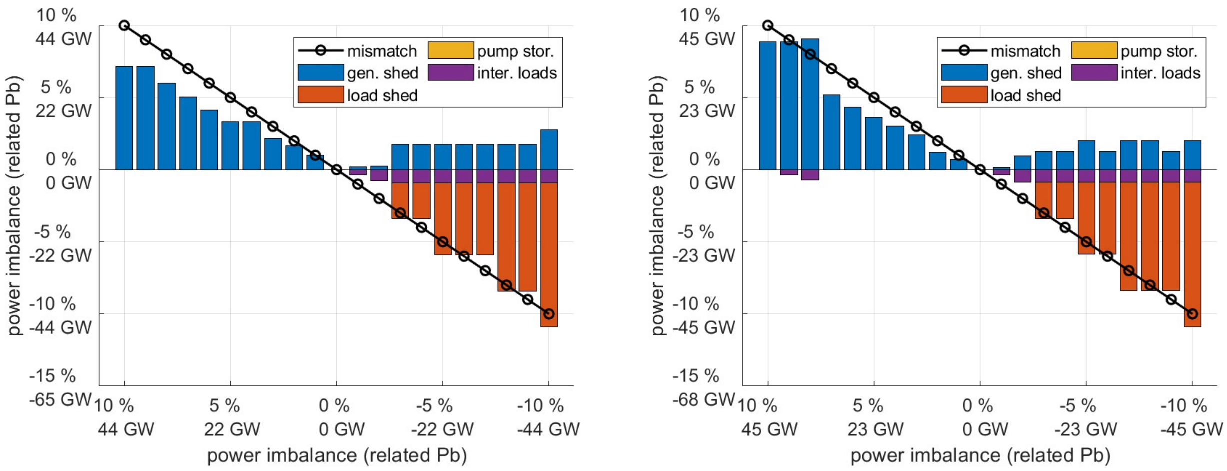

Figure 10: contribution of system defence plan measures towards balancing the initial power imbalance for peak load scenario 2022 (left) and 2030 (right)

Peak RES scenarios

Figure 11 and Figure 12 shows the results of the peak RES scenarios for 2022 and 2030. For all simulated power imbalances, the frequency stays within the acceptable frequency limits. Similarly, to the peak load scenarios, the peak RES scenarios (Figure 12) show a slight decrease in the system's robustness due to the decreasing inertia of the system in 2030. For the 2022 scenario, the maximum

RoCoF is below 1 Hz/s for all considered nonstandard contingencies though. However, due to the decreasing inertia, the RoCoF increases in the 2030 scenario up to 1.6 Hz/s and thus clearly exceeds 1 Hz/s (Figure 13). Only for nonstandard contingencies up to approximately 25 GW the RoCoF stays below 1 Hz/s.

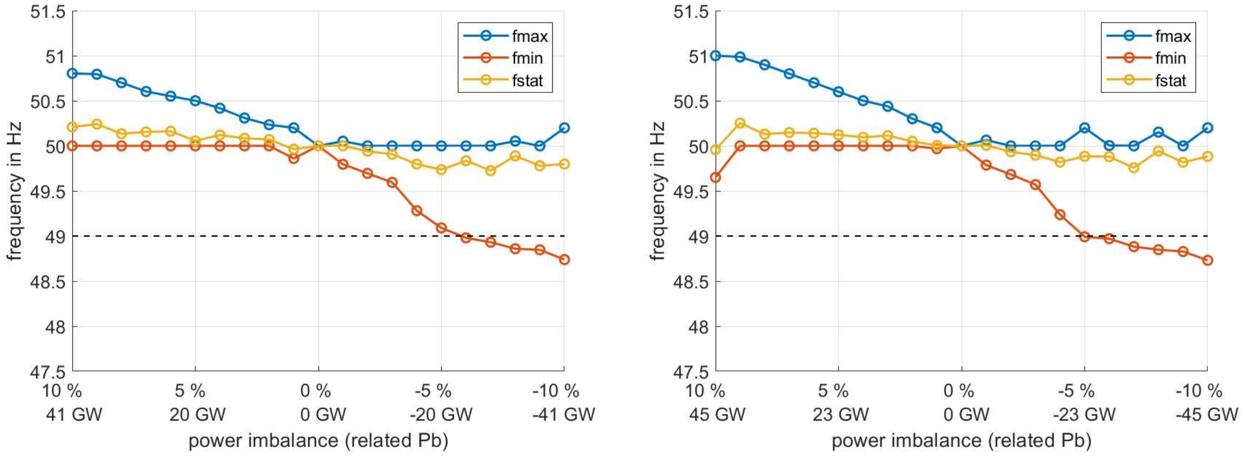

Figure 11: Results for peak RES scenario 2022 (left) and 2030 (right)

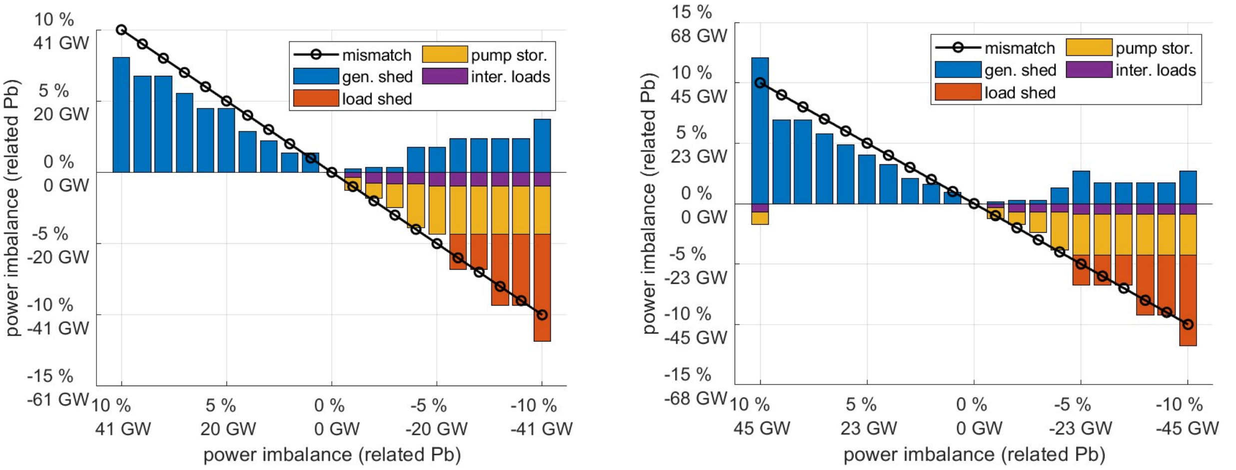

Figure 12: contribution of system defence plan measures towards balancing the initial power imbalance for peak RES scenario 2022 (left) and 2030 (right)

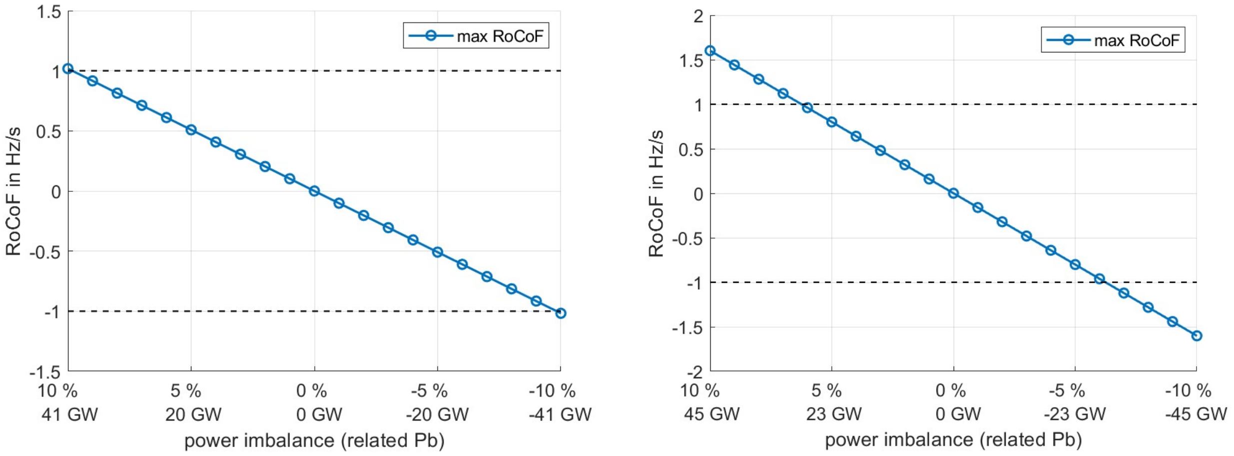

Figure 13: RoCoF values for peak RES scenario 2022 (left) and 2030 (right)

Low load scenarios

Figure 14 shows the evaluation of the simulation results for the low load scenarios. Again, the frequency stays within the frequency limits of 47.5 Hz and 51.5 Hz. However, in contrast to the peak load and peak RES scenarios, no load shedding is triggered in the low load scenarios, since the interruptible loads and under frequency load shedding have a larger impact towards stabilizing the frequency. On the other hand, active power surpluses result in higher over-frequencies compared to the peak load and peak RES scenarios, which finally leads the frequency to increase up to 51.5 Hz. In all simulations the RoCoF was below 1 Hz/s.

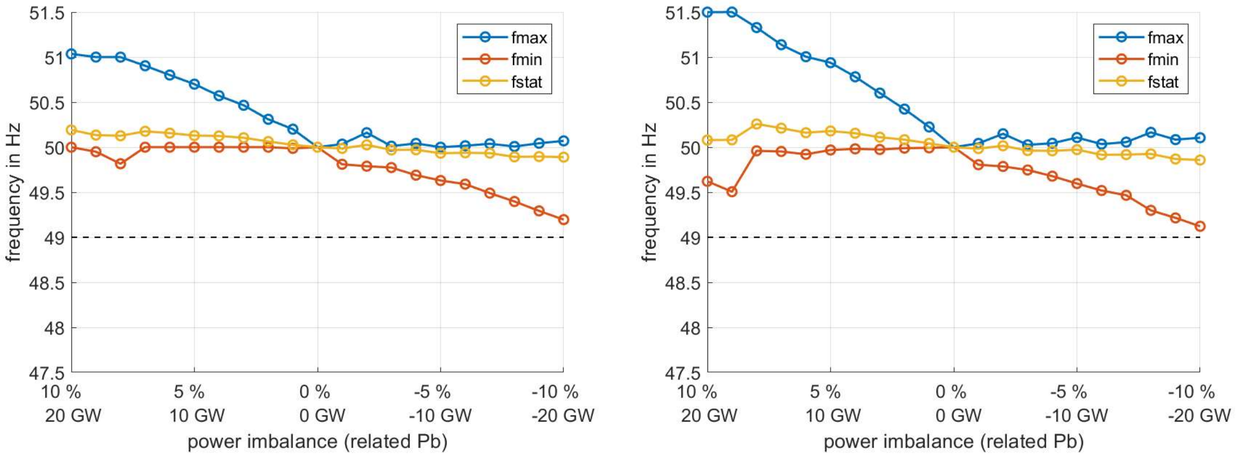

Figure 14: Results for low load scenario 2022 (left) and 2030 (right)

The implemented measures of the system defence plan, consisting of interruptible loads, the disconnection of pump storages in pumping mode and the under frequency load shedding, have a major influence on the controllability of power imbalances. Therefore, in the next steps, for the low load scenarios, the possible impact of absence of interruptible loads and pump storages in pumping mode in the defence plan was analyzed. The related results are shown in Figure 15 and Figure 16, respectively.

It can be observed that the system's robustness significantly decreases, since the frequency already drops below 49 Hz at significantly lower power deficits than when either of these two measures is implemented. Nevertheless, in both cases, the system defence plan works well for power deficits up to 3 GW, which is the dimensioning incident. Hence, the disconnection of interruptible loads and pump storages in pumping mode particularly contributes towards handling larger power imbalances. In addition, the figures show that these measures of the system defence plan might become even more important in the future due to the declining inertia of the system. However, interruptible loads and the disconnection of pump storages do not contribute towards reducing the RoCoF.

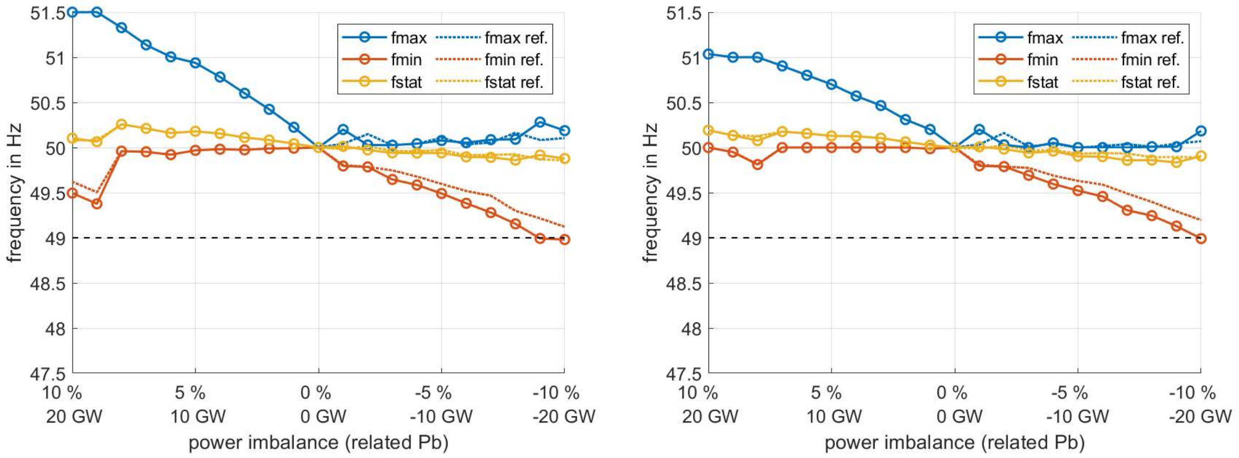

Figure 15: Results for low load scenario 2022 (left) and 2030 (right) without interruptible loads

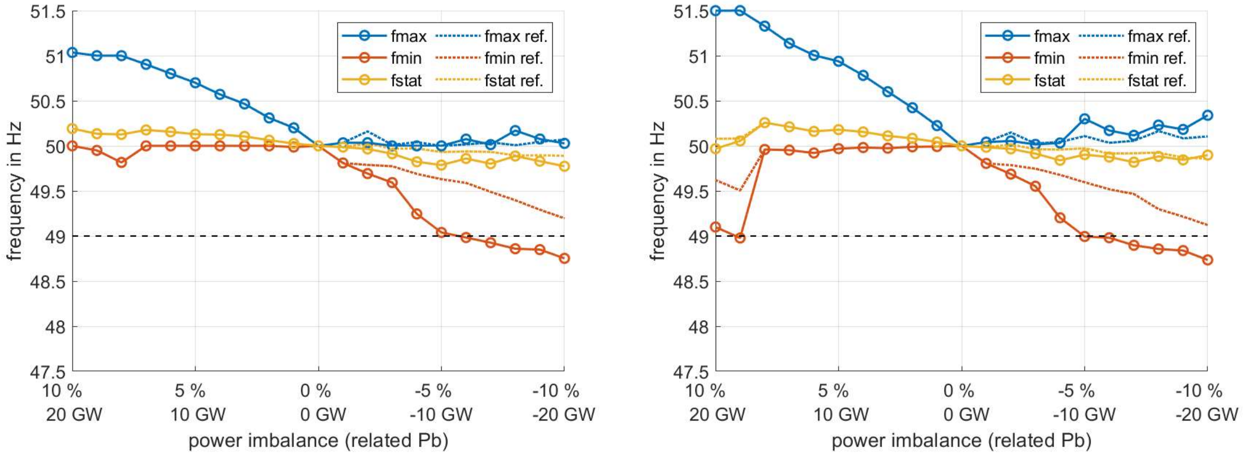

Figure 16: Results for low load scenario 2022 (left) and 2030 (right) without disconnection of pump storages in pumping mode

In the last step, the impact of absence of non-conform generation units and activation of LFSM-O was analyzed.

As it can be seen in Figure 10, the disconnection of non-conform generation units has a positive impact during over-frequency scenarios with a power surplus, since generation units are shed at specific frequency thresholds, whereas they have a negative impact during under frequency scenarios with power deficits, since they counteract load shedding measures. Thus, the system's robustness can be improved if no non-conform generation units are disconnected during under frequency situations. This underlines the importance of grid code compliance of generation units.

However, in order to be able to maintain the frequency within limits during power surpluses if there are no more non-conform generation units, the "limited frequency sensitive mode at over-frequency" (LFMS-O) is a part of the system defence plan. Figure 17 shows the results for the low load scenarios without non-conform generation units, but with activated LFSM-O. This underlines the importance of the LFSM-O in future scenarios considering that non-conform generation units will slowly decrease due to a continuous phase-out of older generation units.

Both, the disconnection of non-conform generation units and activation of LFSM-O have no impact on the occurring maximum RoCoF.

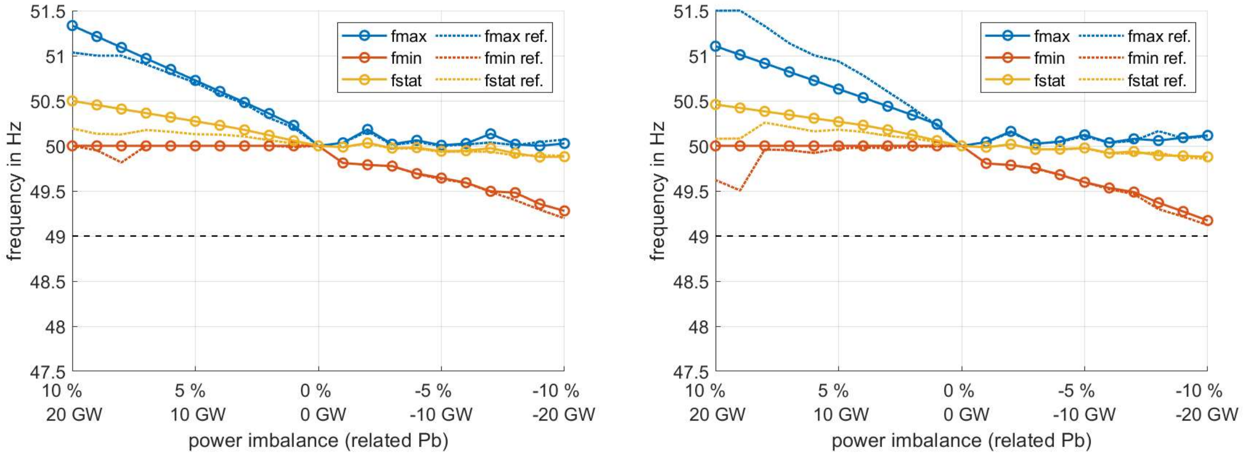

Figure 17: Results for low load scenario 2022 (left) and 2030 (right) with LFSM-O

Conclusion

The goal of this report is to check the validity of the system defence plan of the Continental European synchronous area for peak load, peak RES, and low load scenarios in 2022 and 2030.

A single-busbar model is used to assess the system behavior during severe disturbances. That means, it is assumed that the power system remains interconnected during these disturbances, which include generation and load outages up to 10 % of the total system load. This relates between approximately 20 GW and 44 GW, depending on the scenario, and it is well above the dimensioning incident (3 GW). The parameter which is observed is the system frequency, which represents, based on the model that has been used, the frequency of the 'center of inertia'. Due to the nature of the single-busbar model, other system parameters like voltage are not considered. This is correct because the model must be not influenced by local conditions of the reference system.

The single-busbar model takes into account the influence of: inertia, primary control (FCR), LFSM, the behavior of different generation units and HVDCs, the self-regulating effect of loads, non-conform generation disconnection, interruptible loads/pump disconnections, and the under-frequency load shedding plan.

The performed analyses show that, considering restrictions regarding frequency and RoCoF, the current system defence plan works well for power imbalances up to ± 5 % (Figure 13) of the total system load in 2022 and 2030, assuming that the European power system remains interconnected and the capacity of non-conform generation units do not exceed the values collected among RG CE TSOs. This is also valid for the 2030 scenarios considering the future decrease of the system inertia. In addition, the results show the importance of the implemented measures, such as disconnection of interruptible loads, disconnection of pump storages in pumping mode and activation of LFSM-O, which will become even more important in the future.

The assumption that the European power system remains interconnected is in line with the proper functioning of the system defence plan, as the whole inertia of the system limits the frequency gradient during the first seconds after a disturbance. In addition, the whole of the reserve and system defence plan can be activated.

In this regard, a system split would pose a more severe challenge to the system as, in this case, higher imbalances relative to the size, inertia, reserves, control actions, etc. of separated subsystems can occur. This might be the subject of future studies in this context.

References

[1] ENTSO-E SPD TF Inertia, Inertia and Rate of Change of Frequency (RoCoF), 16.12.2020 [online]

https://eepublicdownloads.azureedge.net/clean-documents/SOC%20documents/Inertia%20and%20RoCoF_v17_clean.pdf

[2] ENTSO-E SPD, Dispersed Generation Impact on CE region security, Dynamic Study, 2014

https://eepublicdownloads.entsoe.eu/clean-documents/Publications/SOC/Continental_Europe/141113_Dispersed_Generation_Impact_on_Continental_Europe_Region_Security.pdf