European Network of
Transmission System Operators
for Electricity

Investigation on Default Underfrequency Support Settings of New Flexibilities in Continental Europe

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From: SG SPD — TF Inertia

ENTSO-E Mission Statement

Who we are

ENTSO-E, the European Network of Transmission System Operators for Electricity, is the association for the cooperation of the European transmission system operators (TSOs). The 39 member TSOs, representing 35 countries, are responsible for the secure and coordinated operation of Europe's electricity system, the largest interconnected electrical grid in the world. In addition to its core, historical role in technical cooperation, ENTSO-E is also the common voice of TSOs.

ENTSO-E brings together the unique expertise of TSOs for the benefit of European citizens by keeping the lights on, enabling the energy transition, and promoting the completion and optimal functioning of the internal electricity market, including via the fulfilment of the mandates given to ENTSO-E based on EU legislation.

Our mission

ENTSO-E and its members, as the European TSO community, fulfil a common mission: Ensuring the security of the inter-connected power system in all time frames at pan-European level and the optimal functioning and development of the European interconnected electricity markets, while enabling the integration of electricity generated from renewable energy sources and of emerging technologies.

Our vision

ENTSO-E plays a central role in enabling Europe to become the first climate-neutral continent by 2050 by creating a system that is secure, sustainable and affordable, and that integrates the expected amount of renewable energy, thereby offering an essential contribution to the European Green Deal. This endeavour requires sector integration and close cooperation among all actors.

Europe is moving towards a sustainable, digitalised, integrated and electrified energy system with a combination of centralised and distributed resources. ENTSO-E acts to ensure that this energy system keeps consumers at its centre and is operated and developed with climate objectives and social welfare in mind.

ENTSO-E is committed to use its unique expertise and system-wide view – supported by a responsibility to maintain the system's security – to deliver a comprehensive roadmap of how a climate-neutral Europe looks.

Our values

ENTSO-E acts in solidarity as a community of TSOs united by a shared responsibility.

As the professional association of independent and neutral regulated entities acting under a clear legal mandate, ENTSO-E serves the interests of society by optimising social welfare in its dimensions of safety, economy, environment, and performance.

ENTSO-E is committed to working with the highest technical rigour as well as developing sustainable and innovative responses to prepare for the future and overcoming the challenges of keeping the power system secure in a climate-neutral Europe. In all its activities, ENTSO-E acts with transparency and in a trustworthy dialogue with legislative and regulatory decision makers and stakeholders.

Our contributions

ENTSO-E supports the cooperation among its members at European and regional levels. Over the past decades, TSOs have undertaken initiatives to increase their cooperation in network planning, operation and market integration, thereby successfully contributing to meeting EU climate and energy targets.

To carry out its legally mandated tasks, ENTSO-E's key responsibilities include the following:

› Development and implementation of standards, network codes, platforms and tools to ensure secure system and market operation as well as integration of renewable energy;

› Assessment of the adequacy of the system in different timeframes;

› Coordination of the planning and development of infrastructures at the European level (Ten-Year Network Development Plans, TYNDPs);

› Coordination of research, development and innovation activities of TSOs;

› Development of platforms to enable the transparent sharing of data with market participants.

ENTSO-E supports its members in the implementation and monitoring of the agreed common rules.

ENTSO-E is the common voice of European TSOs and provides expert contributions and a constructive view to energy debates to support policymakers in making informed decisions.

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List of Abbreviations

Abbreviation	Meaning
CE	Continental Europe
DCC	Demand Connection Code
DSO	Distribution System Operator
ERAA	European Resource Adequacy Assessment
EV	*Electric Vehicle*
GFM	Grid Forming
HP	*Heat Pump*
LFSM-UC	Limited Frequency Sensitive Mode – Underfrequency Consumption
NC ER	Network Code Emergency & Restoration
(NC-)RES	(non-compliant) renewable energy systems
NT	National Trends (one of three TYNDP2022 scenarios)
RfG	Requirements for Generators
RoCoF	Rate of Change of Frequency
S-I	Sensitivity I (S-I…S-IX were investigated)
SBM	System Balance Model
SCR	Short Circuit Ratio
SRL	Self-Regulating (Effect of) Loads
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
UFLS	Under-Frequency Load Shedding (also called conventional load shedding that starts at 49.0 Hz)

Executive Summary

The presented study investigates reasonable default settings for the underfrequency support of new flexibilities for Continental Europe (CE) that are to be defined within RfG 2.0 and the updated DCC. The new flexibilities are namely *Electrical Storages*, *Electric Vehicles*, *Electrolyzers* and *Heat Pumps*. These technologies will be a vital part of the future power system. Because of that, they also need to support the system during and after large disturbances. These devices can support the frequency by dynamically adapting their operating point based on system frequency (also called LFSM-UC) or, in case their reaction time is too slow, they can be shed to decrease system load.

Based on 6 credible TYNDP 2022 CBA scenarios (3 for the timeframe of 2030 and 3 for the timeframe of 2040) a proper use of these flexibilities is investigated using a System Balance Model. The different sensitivities that have been simulated also consider the technical capabilities of each flexibility. Even though LFSM-UC is the preferable choice for *Heat Pumps*, currently it is assumed that *Heat Pumps* have a low flexibility and therefore need to be used as load shedding instead of performing LFSM-UC. In this case, TSOs should have the option, based on technical evidence and risk assessment, to not make use of the load-shedding function completely. All other flexibilities are considered fast enough to be able to perform LFSM-UC. The simulations show that without the use of these flexibilities, disturbances with a RoCoF up to 1 Hz/s can lead to significant conventional load shedding in different scenarios. However, by appropriate use of these flexibilities, the amount of conventional load shedding can be reduced drastically, indicating optimized use of these devices. The simulations show an acceptable system response, especially when LFSM-UC works without hysteresis. By comparing the results of different support settings, it is concluded that the flexibilities are best used as followed:

- *EV*, *Electrolyzers* and *Storages* perform LFSM-UC without hysteresis,
- 5.0 % droop for *EV (*related to $P_{\mathrm{ref}} = P_{\mathrm{act}}$)[1] and *Electrolyzers* (related to $P_{\mathrm{ref}} = P_{\mathrm{act}}$),
- 1.6 % droop for *Storages* (related to $P_{\mathrm{ref}} = P_{\mathrm{max}}$)[2] and
- *Heat Pumps* that are unable to perform LFSM-UC shall be shed between 49.6 Hz…49.1 Hz (6 stages, each 100 mHz).[3] In any case, large industrial *Heat Pumps* will be required to perform LFSM-UC above an installed capacity to be defined by the relevant TSO.

Bearing in mind the potential advantages and disadvantages discussed later in this report, each TSO may request different droops for storages that allow maximization of their power contribution. For storages, even automatically switching to generation mode is possible. Above settings result in reasonable system responses in the year 2030 and year 2040 in all simulated scenarios. SPD therefore recommends implementing these settings as default values in the relevant grid codes *Requirements for Generators* and *Demand Connection Code.*

[1] P_{act} denotes the actual/momentaneous value of the load/infeed.
[2] P_{max} denotes the maximum value/installed capacity of the load/infeed.
[3] If technically possible, *Heat Pumps* shall perform LFSM-UC with 5.0 % droop (related to $P_{\mathrm{ref}} = P_{\mathrm{act}}$), instead of being shed.

Background

Currently the Requirements for Generators (RfG) code and Demand Connection Code (DCC) are being updated. As the power system is expected to change drastically over the upcoming decades, stability measures must constantly be checked, improved and enhanced. New flexibilities—such as controllable loads and generation elements—offer the chance to provide inherent stabilizing capabilities, which are currently delivered by conventional generation elements and renewable energy systems (RES).

This investigation focuses on the support of power system frequency by Limited Frequency Sensitive Mode in the underfrequency consumption mode (LFSM-UC) and load shedding that can be offered by new flexibilities, namely:

- *Storages* (e.g., batteries),
- *Electric Vehicles* (*EV*) with uni- and bi-directional (onboard) chargers,
- *Heat Pumps* (*HP*) and
- *Electrolyzers*.

LFSM in general is the requirement of a power system element to dynamically adapt their load and/or generation according to the system frequency. Thereby the imbalances between total generation and consumption in the grid can be (temporarily) decreased and hence the influence of a disturbance on the frequency can be mitigated.

The goal of this study is to present reasonable default settings for the above-mentioned flexibilities that increase the system’s robustness. Many of these flexibilities will likely not be parametrizable at a later stage, as retrofitting for numerous small, distributed elements is cumbersome and expensive. The focus of the following simulations is on the underfrequency situations and the performance of the underfrequency scheme of the system defence plan. Other measures focusing on a stabilization of the system during overfrequency situations, such as LFSM-O, are not represented.

Moreover, it is important to distinguish between these flexibilities as their response times may vary significantly due to their specific underlying technology. *Heat Pumps*, for example, react much slower than electrical *Storages* and hence a fast adaption of their consumption by LFSM is not considered reasonable.

One important constraint that should also be considered is that the available conventional load-shedding in the 2030 and 2040 scenarios may decrease due to the significant amount of infeed from the distribution grids. This reduces the effective number of loads that can be shed or even prevents certain elements from disconnecting at all.

Thus, a robust scheme for these new flexibilities must be derived and implemented in the grid codes, which is coordinated and properly aligned with other measures of the system defence plan. This report explicitly does not address overfrequency behavior of the system, which will need to be investigated in further studies. Also, the recommendations only apply for CE.

Methodology

Model

The system balance model (SBM), which is regularly used and improved by the SYSTEM PROTECTION AND DYNAMICS (SPD) group during studies, such as [1], is used as a basis for this study. Reference [1] also gives insights into the components of the model, specifically different system defence plan measures that are represented. For the scope of the present study, the components have been extended to implement different schemes for the new flexibilities.

EV, *Storages* and *Electrolyzers* are considered to participate in LFSM-UC schemes, as they are expected to be able to alter their load setpoint quickly and continuously during frequency events. The system balance model was extended with the required LSFM-UC modules to model and test the behaviour of the new flexibilities. Each category (*EVs*, *Storages* and *Electrolyzers*) can be individually parameterized in the model. To be able to study different sensitivities, as described in the Sensitivities chapter of this report, the following LFSM-UC properties can be set using the appropriate model parameters:

- Droop in %: The load setpoint of each group is calculated based on its droop and the frequency deviation.
- Response time in ms: The time required for the flexibility to activate 90 % of its setpoint based on the frequency deviation. In case of hysteresis, the response time can be different for increasing or decreasing LFSM-UC contribution.
- Activation frequency in Hz: The frequency threshold at which the flexibility activates its LFSM-UC contribution. If the frequency falls below this threshold, the flexibility starts to reduce its load based on the droop, frequency deviation and hysteresis setting.
- De-activation frequency in Hz (only in Hysteresis mode): This is the frequency threshold for deactivation of the LFSM-UC contribution in hysteresis mode. Once the frequency rises above this threshold, LFSM-UC mode is deactivated, and the flexibility ramps up its load based on the recovery rate.
- Hysteresis mode: sets whether the hysteresis mode of the LFSM-UC is activated or not. In hysteresis mode, the flexibility starts to reduce its load once frequency falls below the activation frequency and holds its reached maximum load reduction until the frequency rises above the de-activation frequency.

Operation of non-hysteresis and hysteresis modes of the LFSM-UC flexibilities is illustrated in Figure 1 and Figure 2 respectively.

As a conservative assumption, no power reversal of *EVs* and *Storages* is considered. An additional power reversal of these units (particularly bi-directional *EVs* and *Storages*), however, would have a positive impact on the results and improve the resulting frequency trajectories.

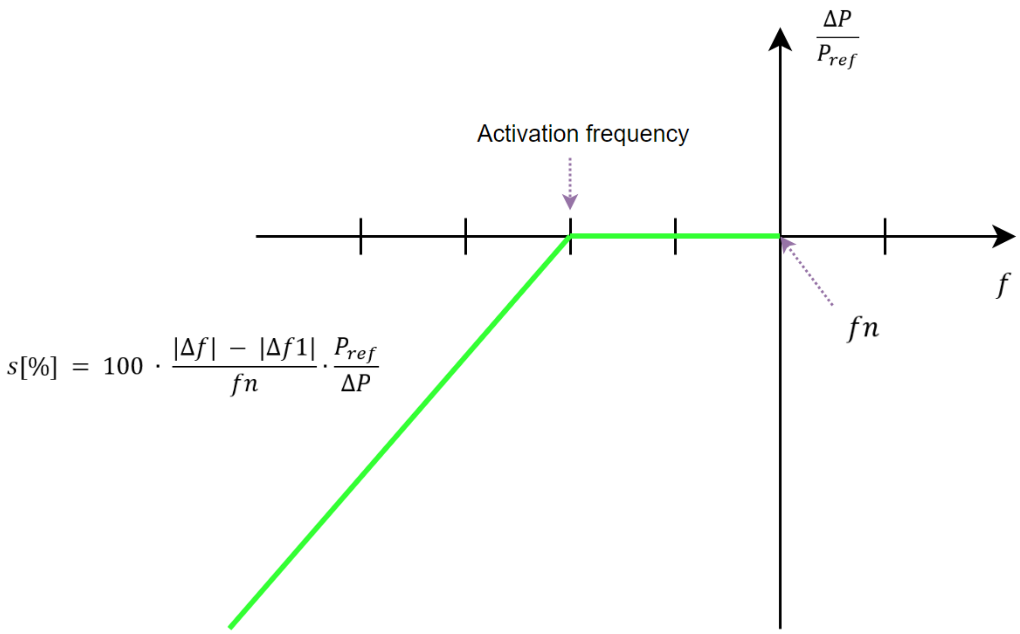

Figure 1:LFSM-U flexibility without hysteresis

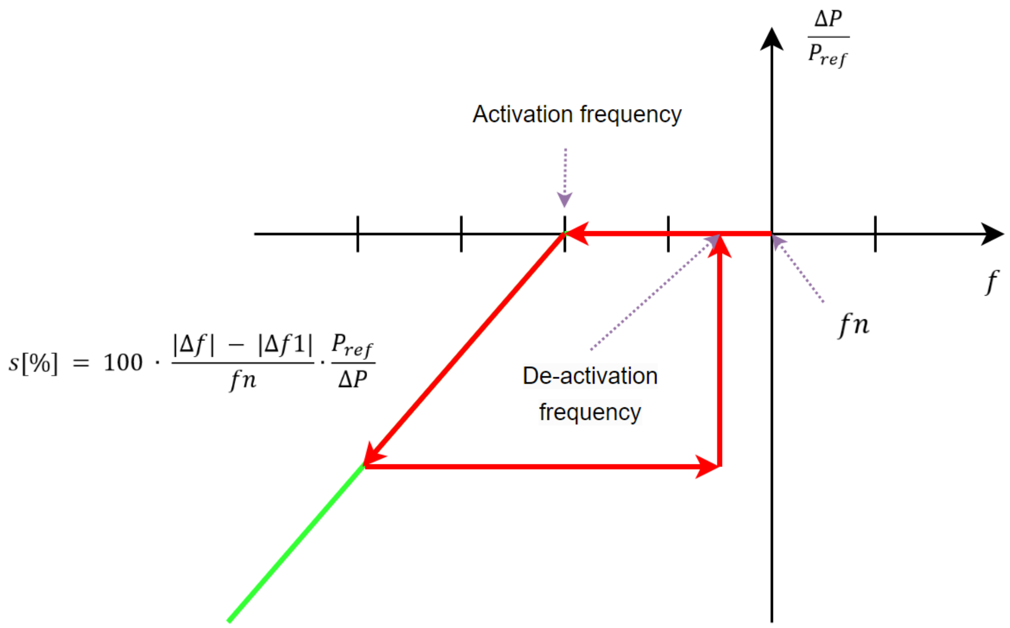

Figure 2: LFSM-U flexibility with hysteresis

Heat Pumps are considered to only be able to contribute as loads that can be disconnected at a predefined frequency threshold. The reason is that their reaction speed (decreasing the load) is not considered to be fast enough to contribute significantly to LFSM-UC. The system balance model was extended with additional LFDD—low frequency demand disconnection—schemes to represent the shedding of *Heat Pumps*. In each scenario, the total load representing *Heat Pumps* was divided and equally distributed to different stages, with individual frequency disconnection thresholds. The number of stages and their assigned frequency thresholds can be altered to allow the investigation of different *Heat Pump* disconnection strategies.

One important constraint of this model, which needs to be considered when analysing the results, is that UFLS (under-frequency load shedding; here, also called conventional load shedding) has no impact on the flexibilities. A considerable amount of the herein investigated flexibilities are connected to the DSO grids. UFLS affects the DSO grid and hence would also affect the capabilities of these flexibilities. As later seen, this simplification is justified, as the flexibilities are effective mostly before UFLS is even triggered.

Also, it must be considered that the used system balance model reflects only the frequency response of the system in the centre of inertia. Effects and instabilities due to low inertia or low SCR may not be visible in the results. Consequently, more detailed stability analysis for regions with low inertia or SCR are necessary and must be conducted by the corresponding TSOs, in order to ensure a stable system behaviour. Furthermore, effects due to controller interactions and/or frequency estimation issues (e.g., due to (inter-)harmonics) are also not reflected in the used system balance model.

Scenarios

As input data for the SBM, the 2022 Ten-Year Network Development Plan (TYNDP) CBA market data is used, specifically the National Trends (NT) Scenarios. Consistent with [2], the Climate Year 2009 is used. In each of the investigated scenarios, the inertia constant H lies well within the projected TYNDP2022 inertia duration curves of [2]. Data for *EV* and *Heat Pumps* was obtained by public ERAA 2023 data [3] and extrapolated to represent missing countries.

Based on this data, credible scenarios (hours) were chosen to perform the subsequent investigations. From the estimated amount of flexibilities connected to the grid in each scenario, only a limited part was assumed to be already RfG 2.0 compliant. In 2030, one-third (1/3) of *Storages*, *EV* and *Heat Pumps* were considered to be compliant to RfG 2.0. For *Electrolyzers* it was assumed that already two-thirds (2/3) will be RfG 2.0 compliant as their large-scale expansion is planned to happen mostly within this decade. In the year 2040 it was assumed that two-thirds (2/3) of S*torages*, *EV* and *Heat Pumps* are compliant and eight-tenths (8/10) of *Electrolyzers*.

To properly assess the performance of the schemes, it is important to consider different system states. For both timeframes—year 2030 and year 2040—a “High Load”, “Low Load” and “Peak RES” scenario is investigated. The scenarios and used simulation parameters are shown in Table 1.

Additional inertia support from Grid Forming (GFM) converters, HVDCs and assets like STATCOMs with storages or synchronous condensers is not part of the TYNDP data and hence neglected in this study. Available amounts of additional inertia in the scenarios would decrease the initial rate of change of frequency (RoCoF) and increase frequency stability and the robustness of defence plan in general. Sufficient inertia is also necessary to keep the RoCoF within a manageable range for different imbalance sizes. Inertia needs required for a stable system response are currently investigated in Project Inertia Phase II [4]. Regarding available inertia, the simulations can hence be considered conservative, particularly in the year 2040.

Table 1: Overview of scenarios and parameters used in the simulation model; new flexibilities in blue (only the RfG 2.0 compliant amount is given in the table)

	Unit	Scenario A: "High Load"	Scenario B: "Low Load"	Scenario C: "Peak RES"	Scenario D: "High load"	Scenario E: "Low load"	Scenario F: "Peak RES"
TYNDP Target Year	(yr)	2030	2030	2030	2040	2040	2040
TYNDP Scenario		NT	NT	NT	NT	NT	NT
Load	(GW)	520	260	400	580	290	500
Storages (compliant)	(GW)	7	0	7	23	10	23
EV (compliant)	(GW)	15	15	7	65	65	25
Heat Pumps (compliant)	(GW)	35	10	15	100	30	40
Electrolyzers (compliant)	(GW)	14	0	14	50	15	50
PV	(GW)	100	0	160	170	0	250
Wind	(GW)	100	40	120	200	100	150
Gas	(GW)	80	20	30	100	50	50
SRL	(%/Hz)	2.0	2.0	2.0	1.5	1.5	1.5
Simultaneity factor pumps	(%)	0	40	50	0	40	50
Simultaneity factor NC-RES	(%)	30	5	40	0	0	0
max. effective conventional load shed (of total load)	(%)	38	45	30	38	45	25
inertia constant H calculated for the system	(s)	2.46	3.38	1.20	1.45	2.62	0.80

Disturbances

The focus of this study is to provide reasonable settings for the flexibilities for the underfrequency regime (frequencies below 50 Hz). To test this part of the system defence plan, losses of generation are applied. The size of the imbalance is scenario-specific and chosen to cause a RoCoF of approximately 1 Hz/s. Figures on page 12 of [2] show exemplary ranges of contingencies that lead to 1 Hz/s RoCoFs. The upper threshold of 1 Hz/s can still be handled reasonably by the system defence plan [5], [6], [7]. The reason for imposing 1 Hz/s as an upper limit is that countermeasures, as conventional load shedding for example, require sufficient time to react upon the disturbance and avoid over-shedding. Also, larger RoCoFs may lead to cascading trips of generation units. It shall be noted that the simulated disturbances of many GWs that lead to 1 Hz/s RoCoFs in the scenarios, are expected to be very rare in the future, just as they have been in the past. Recommended schemes are therefore only very rarely expected to be triggered.

Sensitivities

The goal of the usage of these new flexibilities is that they shall support the power system stability and avoid conventional load shedding as far possible as this means interruption of supply for customers. Hence, these new flexibilities need to be effective before the activation of conventional load shedding (at 49.0 Hz). Under this premise, different settings of LFSM-UC and different settings for the shedding of *Heat Pumps* (called sensitivities) are introduced hereafter and investigated in the following.

Sensitivity I (S-I) is used as a base case scenario, without any contribution from the new flexibilities. Other sensitivities, representing the effect and contribution of the new flexibilities, can be compared to this sensitivity.

Sensitivity II and III (S-II and S-III) represent cases, with and without hysteresis mode respectively, where LFSM-UC droop is universally set to 5 %, a well-established value across the industry. LFSM-UC is activated at 49.8 Hz and in case of hysteresis mode, deactivated once the frequency reaches 49.95 Hz again. *Heat Pumps* are divided into 6 shedding stages and are disconnected between 49.6 Hz and 49.1 Hz, in 0.1 Hz increments.

In case of Sensitivity IV and V, LFSM-UC settings are identical to Sensitivities II and III but shedding of *Heat Pumps* is not considered.

Sensitivity VI and VII represent cases, with and without hysteresis mode respectively, where LFSM-UC droop is universally set to 1.6 %, a rather ambitious value that results in higher contribution provided by *EVs*, *Storages* and *Electrolyzers*. LFSM-UC is activated at 49.8 Hz and in case of hysteresis mode, deactivated once the frequency reaches 49.95 Hz again. *Heat Pumps* are divided into 6 shedding stages and are disconnected between 49.6 Hz and 49.1 Hz, in 0.1 Hz increments.

Sensitivity VIII and IX represent cases, with and without hysteresis mode respectively. In these sensitivities, LFSM-UC droop is set to an ambitious value of 1.6 % for *Storages*, as these are anticipated to be installed mainly as grid scale assets and can react very fast. LSFM-UC droop setting of *EVs* and *Electrolyzers* are chosen to be the well-established 5 %, as *EV*s will be connected to the utility grid and the response time of *Electrolyzers* is higher than those of *Storages*. LFSM-UC is activated at 49.8 Hz and in case of hysteresis mode, deactivated once the frequency reaches 49.95 Hz again. *Heat Pumps* are divided into 6 shedding stages and are disconnected between 49.6 Hz and 49.1 Hz, in 0.1 Hz increments.

For all sensitivities with hysteresis activated, the response time after deactivation of LFSM-UC (at 49.95 Hz, was set to approx. 0.033 pu/min, so that the power drawn from those devices only comes back very slowly. This small slope is nearly irrelevant in the 60 s simulation timeframe.

Detailed settings of the investigated sensitivities (S-I to S-IX) are listed in Table 2 and Table 3.

Table 2: Investigated Sensitivities – Part 1

Device	Setting	Unit	S-I	S-II	S-III	S-IV	S-V
Storages & EV	Hysteresis		-	Yes	No	Yes	No
	Droop	(%)	-	5.0	5.0	5.0	5.0
	Response Time	(ms)	-	500	500	500	500
	Activation Frequency	(Hz)	-	49.80	49.80	49.80	49.80
	De-activation Frequency	(Hz)	-	49.95	-	49.95	-
Heat Pumps	Disconnection Frequency Range (Hz)	(Hz)	-	49.6…49.1 (in 6 stages)	49.6…49.1 (in 6 stages)	-	-
	Disconnection Time	(ms)	-	300	300	-	-
Electrolyzers	Hysteresis		-	Yes	No	Yes	No
	Droop	(%)	-	5.0	5.0	5.0	5.0
	Response Time	(ms)	-	3 000	3 000	3 000	3 000
	Activation Frequency	(Hz)	-	49.80	49.80	49.80	49.80
	De-activation Frequency	(Hz)	-	49.95	-	49.95	-

Table 3: Investigated Sensitivities – Part 2

Device	Setting	Unit	S-VI	S-VII	S-VIII	S-IX
Storages & EV	Hysteresis		Yes	No	Yes	No
	Droop	(%)	1.6	1.6	*Storages*: 1.6 *EVs*: 5.0	*Storages*: 1.6 *EVs*: 5.0
	Response Time	(ms)	500	500	500	500
	Activation Frequency	(Hz)	49.80	49.80	49.80	49.80
	De-activation Frequency	(Hz)	49.95	-	49.95	-
Heat Pumps	Disconnection Frequency Range	(Hz)	49.6...49.1 (in 6 stages)	49.6...49.1 (in 6 stages)	49.6...49.1 (in 6 stages)	49.6...49.1 (in 6 stages)
	Disconnection Time	(ms)	300	300	300	300
Electrolyzers	Hysteresis		Yes	No	Yes	No
	Droop	(%)	1.6	1.6	5.0	5.0
	Response Time	(ms)	3 000	3 000	3 000	3 000
	Activation Frequency	(Hz)	49.80	49.80	49.80	49.80
	De-activation Frequency	(Hz)	49.95	-	49.95	-

Simulation Results

All sensitivities (see Table 2 and Table 3) were simulated for all scenarios. In the following, only a set of relevant cases are selected for display. The figures always show the frequency trajectory for only one timeframe (2030 or 2040) but for all three scenarios ("Peak Load", "Low Load" and "Peak RES").

The results are evaluated based on multiple indicators. One of the main indicators to assess the performance of a sensitivity is the amount of conventional load shedding that is activated. Conventional load shedding is considered as a last resort and will ultimately lead to an interruption of supply for consumers. The reduction of the amount of conventional load shedding—and hence the blackout of certain parts of the network—is a priority. In addition to that, special focus lies on the evaluation of the:

- amount of over-shedding / over-shoot,
- extent of dynamic frequency excursions,
- steady-state frequency after the disturbance and
- activated amount of frequency containment reserve (FCR), pumps disconnected, interruptible loads disconnected, LFSM-UC activated, and amount of *Heat Pumps* shed.

Figure 3 shows the reference frequency trajectories for 2030 in case no flexibilities are used and represents the state of the art without any additional LFSM-UC contribution. Below 49.0 Hz, conventional load shedding is activated to bring the frequency back up. In the peak load scenario (blue curve) approximately 50 GW load is shed. This is equivalent to the peak load of Italy or could alternatively translate to a blackout for approximately 50-60 million people.

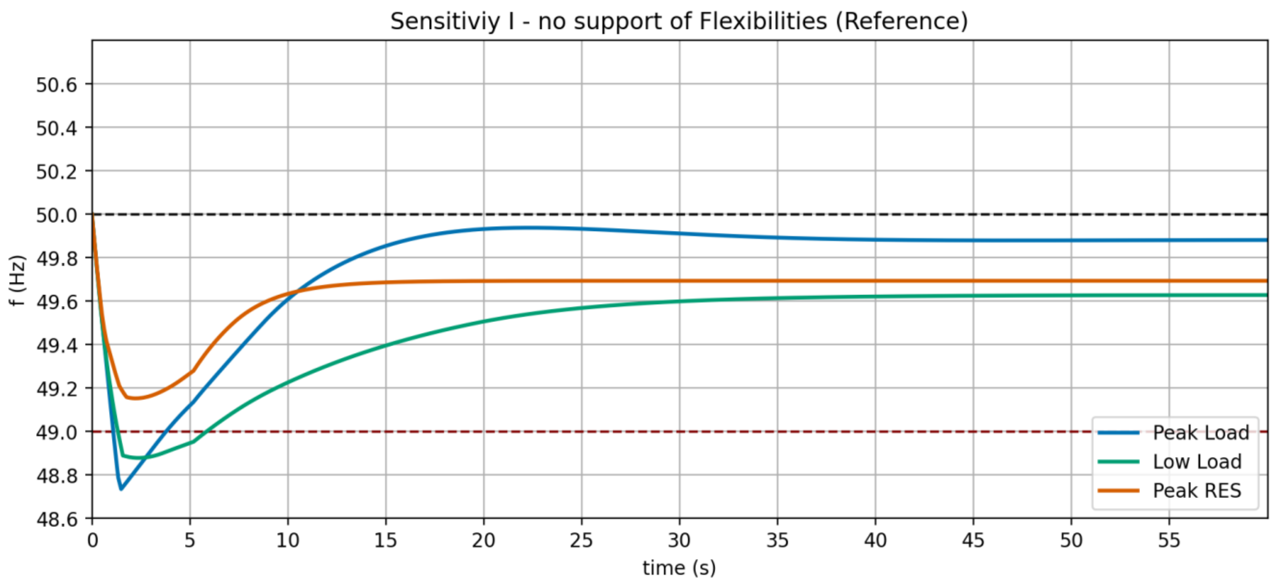

Figure 3: S-I reference (NT 2030)

The following sensitivities that use the new flexibilities try to reduce the amount of conventional load shedding. Figure 4 and Figure 5 show the 2030 cases, where *Heat Pumps* are shed between 49.6 Hz and 49.1 Hz and a common droop of 5 % is used for LFSM-UC. Figure 4 shows the frequency trajectories with hysteresis activated and Figure 5 shows the behaviour without hysteresis.

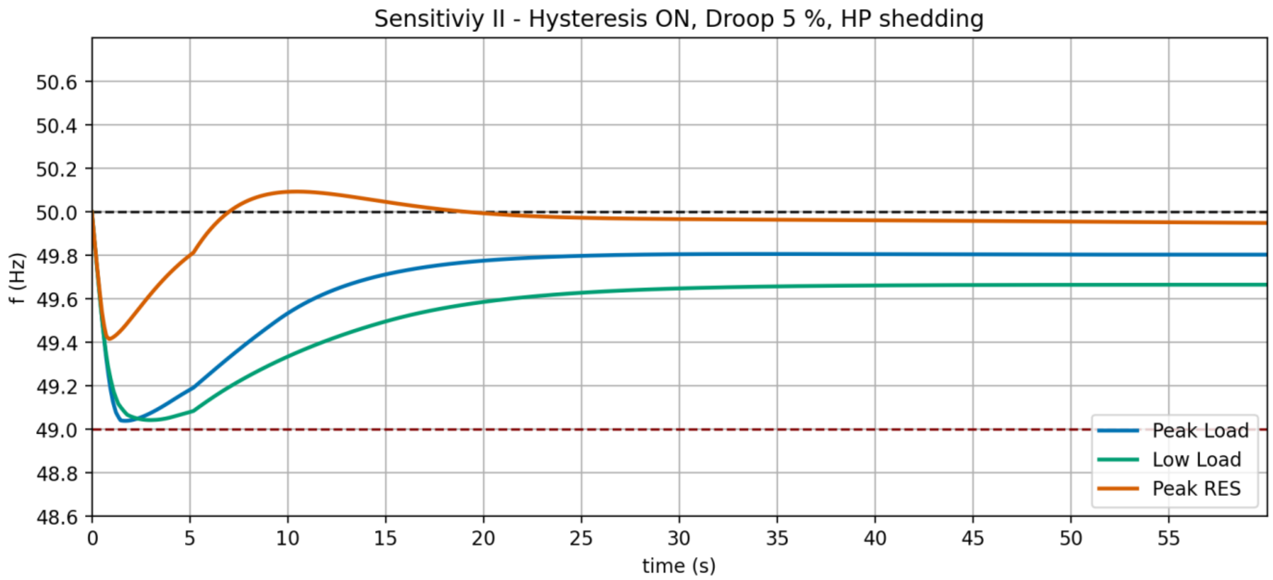

Figure 4: S-II sensitivity (NT 2030)

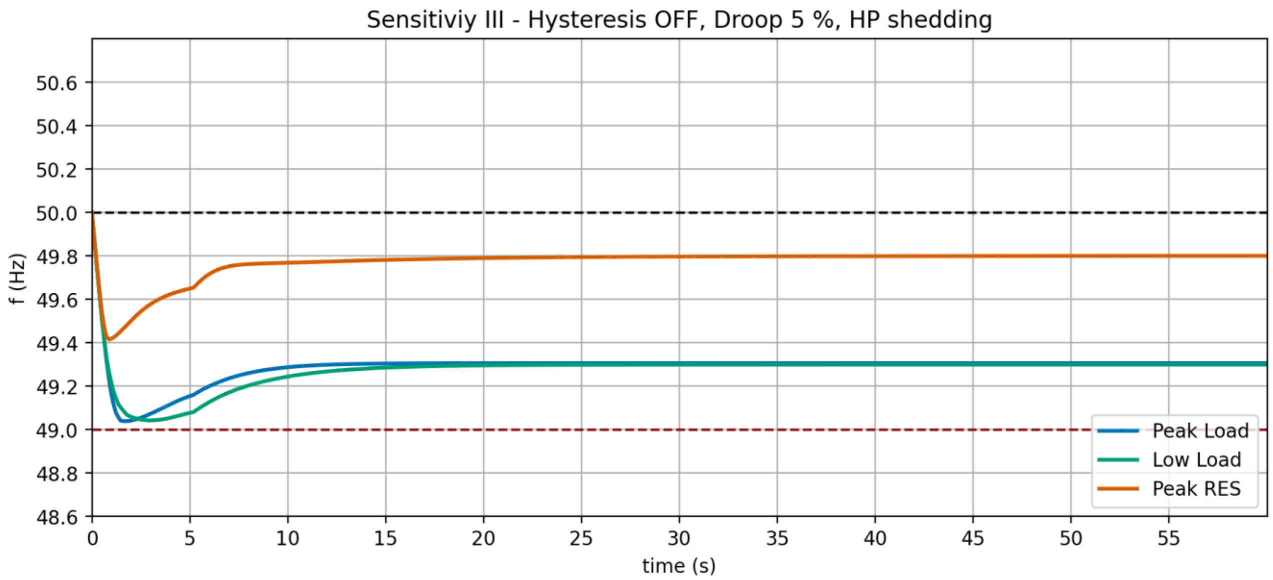

Figure 5: S-III sensitivity (NT 2030)

In both cases conventional load shedding is prevented as the frequency does not reach below 49.0 Hz. It can also be seen that, due to the temporary deactivation of loads, with hysteresis activated, the frequency rises closer to 50.0 Hz. All system responses are considered acceptable.

Figure 6 and Figure 7 show the 2030 cases, where *Heat Pumps* are also shed between 49.6 Hz and 49.1 Hz but a common droop of 1.6 % is used for LFSM-UC. Figure 6 shows the frequency trajectories with hysteresis activated and Figure 7 shows the behaviour without hysteresis.

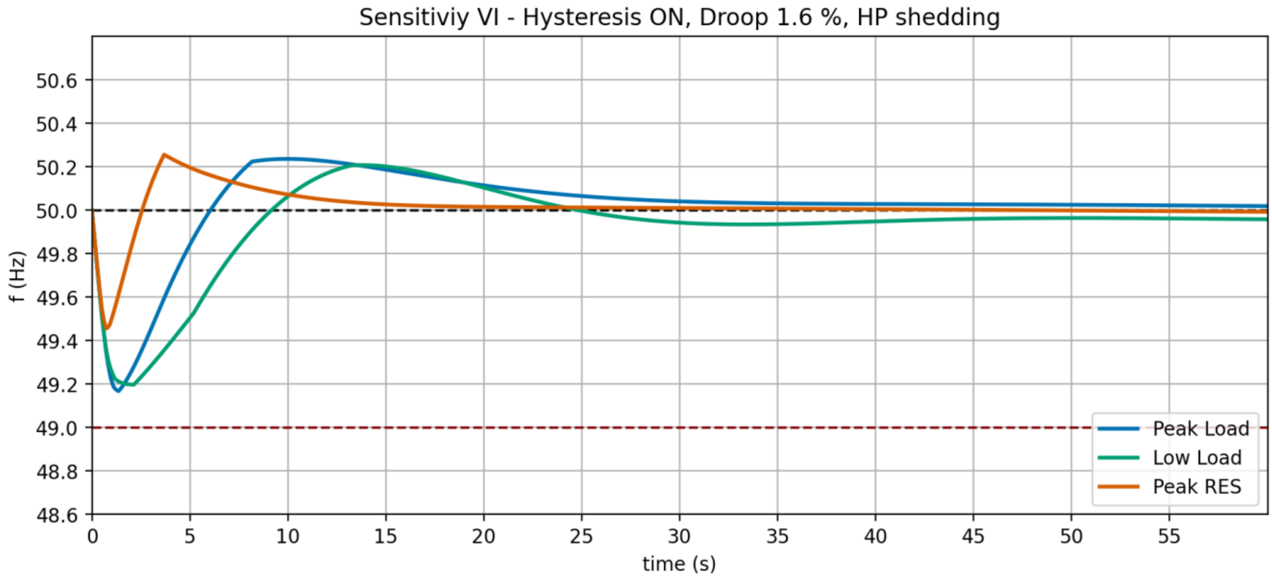

Figure 6: S-VI sensitivity (NT 2030)

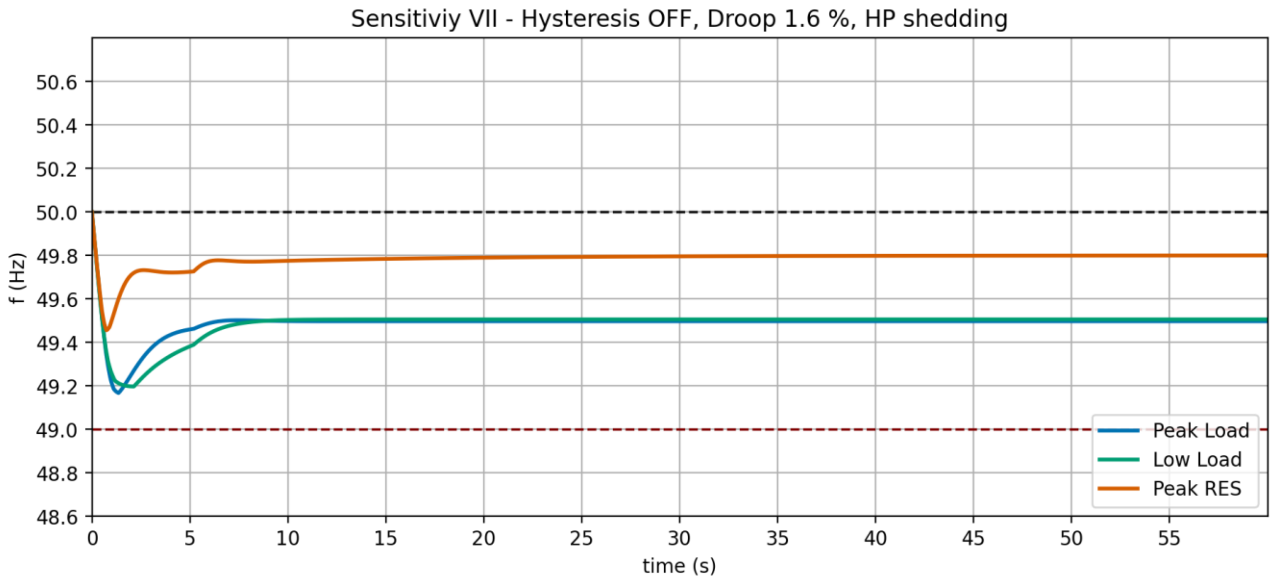

Figure 7: S-VII sensitivity (NT 2030)

Also in these cases, conventional load shedding is avoided. Compared to 5 % droop (see Figure 4 and Figure 5), the frequency nadir is slightly higher. As in the previous example, activated hysteresis brings the frequency closer back to 50.0 Hz. However, here it also results in slight over-shedding and therefore disconnection of non-compliant RES at 50.2 Hz. All system responses are acceptable.

Figure 8 and Figure 9 show the 2030 cases, where *Heat Pumps* are shed between 49.6 Hz and 49.1 Hz and a droop of 1.6 % is used for *Storages* and 5 % is used for *EV* and *Electrolyzers*. Figure 8 shows the frequency trajectories with hysteresis activated and Figure 9 shows the behaviour without hysteresis.

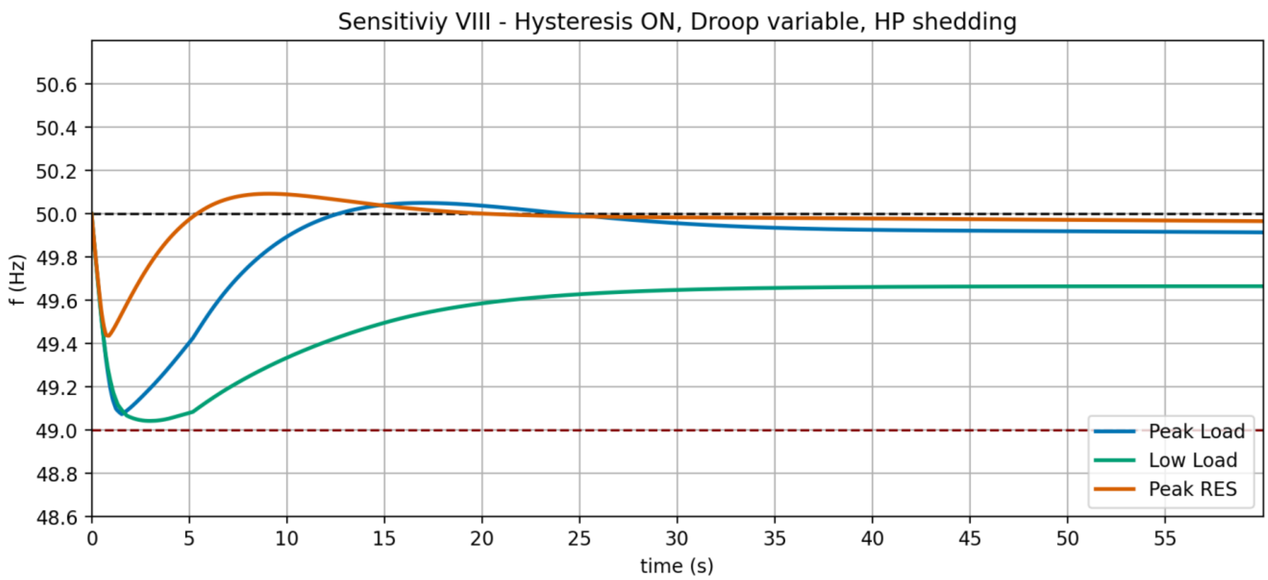

Figure 8: S-VIII sensitivity (NT2030)

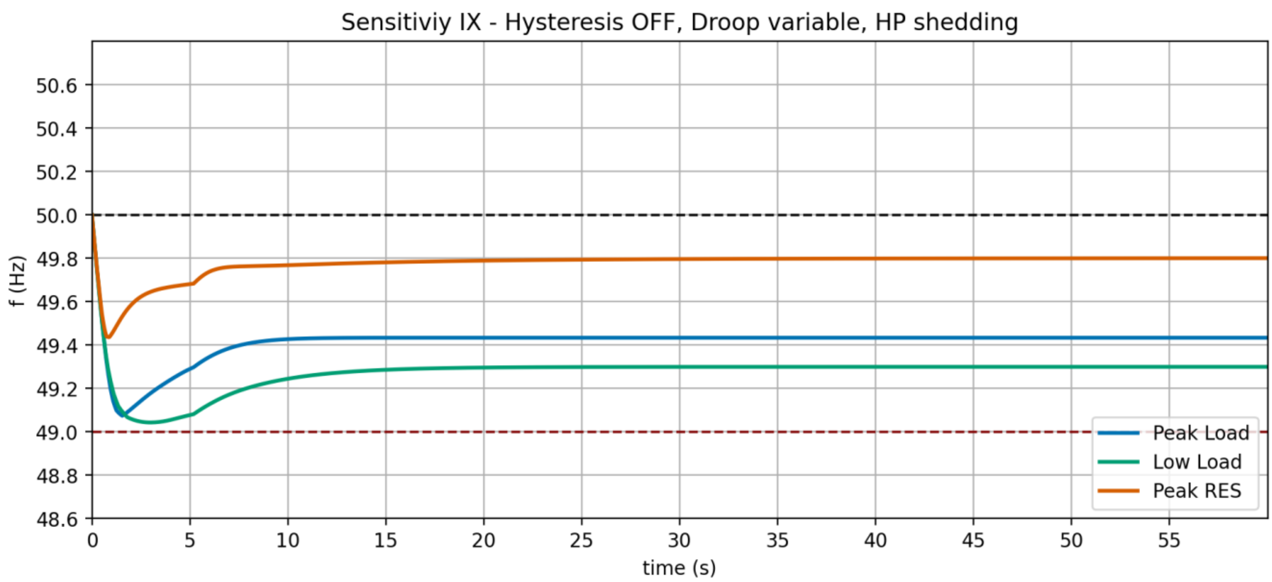

Figure 9: S-IX sensitivity (NT2030)

Conventional load shedding is again prevented. Also, activated hysteresis brings the frequency closer back to 50.0 Hz. All system responses are considered acceptable.

The 2040 results are consistent with the results shown here and briefly discussed later.

Recommendation

The following settings investigated in sensitivity S-IX are recommended to be implemented in future flexibilities:

- no hysteresis,
- 5.0 % droop for *EV* (related to $P_{\mathrm{ref}} = P_{\mathrm{act}}$)[4] and *Electrolyzers* (related to $P_{\mathrm{ref}} = P_{\mathrm{act}}$),
- 1.6 % droop for *Storages* (related to $P_{\mathrm{ref}} = P_{\mathrm{max}}$)[5] and
- *Heat Pumps* that are unable to perform LFSM-UC shall be shed between 49.6 Hz…49.1 Hz (6 stages at: 49.6 Hz, 49.5 Hz, 49.4 Hz, 49.3 Hz, 49.2 Hz and 49.1 Hz).[6] In any case, large industrial *Heat Pumps* will be required to perform LFSM-UC above an installed capacity to be defined by the relevant TSO.

Bearing in mind the potential advantages and disadvantages discussed in this report, each TSO may request different droops for storages that allow maximization of their power contribution. For storages, even automatically switching to generation mode is possible.

Heat Pumps that are not able to perform LFSM-UC, act as uncontrolled loads. The power system will be penetrated by millions of *Heat Pumps* in the upcoming decades. Opposite to controlled loads (loads that can perform LFSM-UC), uncontrolled loads pose a higher risk to lead to over-shedding and hence over-frequencies. To understand and study their future impact on the power system, it will be necessary that vendors track and transparently share information at least the following information for each installed *Heat Pump*: installed capacity, randomly set frequency threshold for disconnection (between 49.6…49.1 Hz) and country of installation.

Reasoning for the Selected Values

Heat Pump Shedding in 6 Stages between 49.6 Hz … 49.1 Hz:

Waiting for conclusions about the technical capabilities of *Heat Pumps* to regulate their power in proportion to the temperature setpoint, the current report makes the assumption that the current NC DC proposal would lead to a sudden deactivation of a *Heat Pump* and hence behave as load shedding. Therefore, it is recommended to describe it in a simpler manner directly as frequency-dependent shedding.

For large disturbances, the upper value of 49.8 Hz would be more beneficial, because *Heat Pumps* would be shed at an earlier point in time. Nevertheless, the design incident of 3000 MW outage ideally should be handled without load shedding, just by using FCR. During this event, the frequency can transiently swing under 49.8 Hz. Defining the first stage of shedding at 49.6 Hz and not at 49.8 Hz prevents, at least in most cases, *Heat Pump* shedding in case of the 3000 MW outage. This is a

[4] P_{act} denotes the actual/momentaneous value of the load/infeed.
[5] P_{max} denotes the maximum value/installed capacity of the load/infeed.
[6] If technically possible, *Heat Pumps* shall perform LFSM-UC with 5.0 % droop (related to $P_{\mathrm{ref}} = P_{\mathrm{act}}$), instead of being shed.

compromise which results in an acceptable behaviour in both situations. The lower threshold of 49.1 Hz is selected in order to avoid as much as possible the conventional load shedding, which causes a stronger impact to society, starting at 49.0 Hz. TSOs may increase the number of shedding stages above 6, if a finer distribution of *Heat Pump* shedding is needed.

Because of the vast number of small devices, the reconnection cannot be performed manually by the power system operator. Thus, the reconnection must be automatic. The definition of the settings for the automatic reconnection is not part of this study, because this is an aspect that influences mainly the process of system restoration. This should be discussed with the experts of this domain. Therefore, no dedicated recommendation is given. However, the resulting approach shall be subsequently assessed with the help of dynamic model simulation too. One reasonable approach would be to have a randomized delayed reconnection, once the frequency has restored in the range of 50 Hz ± 200 mHz starting not earlier than 2 hours after the disturbance[7]. Thereby, system operators have sufficient time to synchronize islanded systems and/or bring the frequency back up after larger disturbances, without unknown amounts of *Heat Pumps* reconnecting to the network and intervening with their operation.

<u>No Hysteresis:</u>
The sensitivities with hysteresis tend to produce overshooting towards overfrequency behaviour. This is because of an overreaction in the reduction of the power consumption due to the internal delays of the device, which cannot be avoided. Therefore, the LFSM-UC with hysteresis needs the LFSM-O scheme in closed loop or the shedding of power generating facilities to stabilize the frequency. Because it is highly desirable that the LFSM-UC scheme is working properly without the help of another scheme, implemented in other devices, a hysteresis is not recommended. Furthermore, the increase of the power consumption after the event must be performed in a similar automatic way as for the *Heat Pump* shedding, i.e., randomized time delay, when frequency has stabilized around 50 Hz. This is difficult to handle for the system operator during system restoration because the system operator has no means to influence it and possibly no exact knowledge about the amount of load that comes back. For *Heat Pump* shedding, this cannot be avoided, but for LFSM-UC it is influenceable.

In contrast, a closed loop LFSM-UC scheme moving up and down the droop continuously, is stabilizing the frequency on its own and is responding promptly to the operator's actions during system restoration in a predictable manner. A downside of not using hysteresis is possible long-lasting low frequencies that need to be mitigated by the system operator. For a portion of the network at the border of the synchronous area, which can be subjected to island formation, the use of hysteresis can be an option evaluated by the TSO.

[7] E.g., after being shed, each *Heat Pump* stays disconnected for 2 h. If the frequency is back in the normal range, it reconnects to the system with a randomized time delay between 0 and 2 h (slowly ramping up to its initial, pre-fault operating point).

Droop Values:
Small droop values mean:

- a large adaption of the power consumption for a given frequency deviation, i.e., a large contribution to the compensation of the imbalance, which has a positive effect and
- a high amplification of the control loop, which is reducing the damping and usually has a negative impact.

For large droop values, the opposite applies. The selection of the droop values shall find a compromise between the two effects.

Storages in charging mode cannot only reduce their power consumption, but also — depending on their state of charge — switch to infeed. This increases their potential for helping to compensate the power imbalance in the system, compared to pure consumption devices. To make this potential usable for LFSM-UC, the droop shall be set to a small value. Therefore, the recommended droop for *Storages* is 1.6 %, which allows a reduction of the power consumption to zero at 49 Hz. Thus, this scheme is compliant with Network Code Emergency & Restoration (NC ER) Article 15 (3)[8]. Based on a TSO's assessment, storages can be equipped with control schemes able to maximize the power contribution provided in underfrequency operation, even automatically switching to generation mode. In order to avoid bad damping in the system, considering large amounts of loads contributing to LFSM-UC in the future, the proposed droop for *EVs* and *Electrolyzers* is set to 5 %. Large and fast changes in the load flow on the distribution network could cause difficulties, since voltage control reacts relatively slow. Large amounts of *EVs* connected to the low voltage distribution network with a low droop setpoint could interfere with these controllers. A deeper understanding of the effect of these interactions would require a detailed study, which is outside the scope of this report. As *Electrolyzers* react slower to load setpoint changes than *EVs* and *Storages*, a small droop setpoint could result in controller instability. The 5 % droop setpoint, as recommended for these devices, is a widely used setting and can possible mitigate the above-mentioned concerns.

In case *Heat Pumps* are able to perform LFSM-UC, to be effective, their response times shall be comparable to the response times required for *EV*, *Storages* and *Electrolyzers* (less than a few seconds).

[8] NC ER Article 15 (3) states:
Prior to the activation of the automatic low frequency demand disconnection scheme, each TSO and DSO identified pursuant to Article 11(4) shall foresee that energy storage units acting as load connected to its system:
(a) automatically switch to generation mode within the time limit and at an active power set-point established by the TSO in the system defence plan; or
(b) when the energy storage unit is not capable of switching within the time limit established by the TSO in the system defence plan, automatically disconnect the energy storage unit acting as load.

Additional Sensitivities for Recommendation

In addition to the sensitivities shown in the Simulation Results section, additional studies were performed on the recommended sensitivity to underline the robustness of the recommendation.

Generally, it can be observed that the sensitivities with activated hysteresis lead to much larger over-shedding (overfrequency) on the 2040 timeframes. This strengthens the position of not using hysteresis, as underfrequency should not lead to overfrequency due to an overreaction of the system defence plan. Figure 10 shows the results for the 2040 case of the recommended sensitivity S-IX. It can be seen that also on this timeframe this sensitivity performs very well.

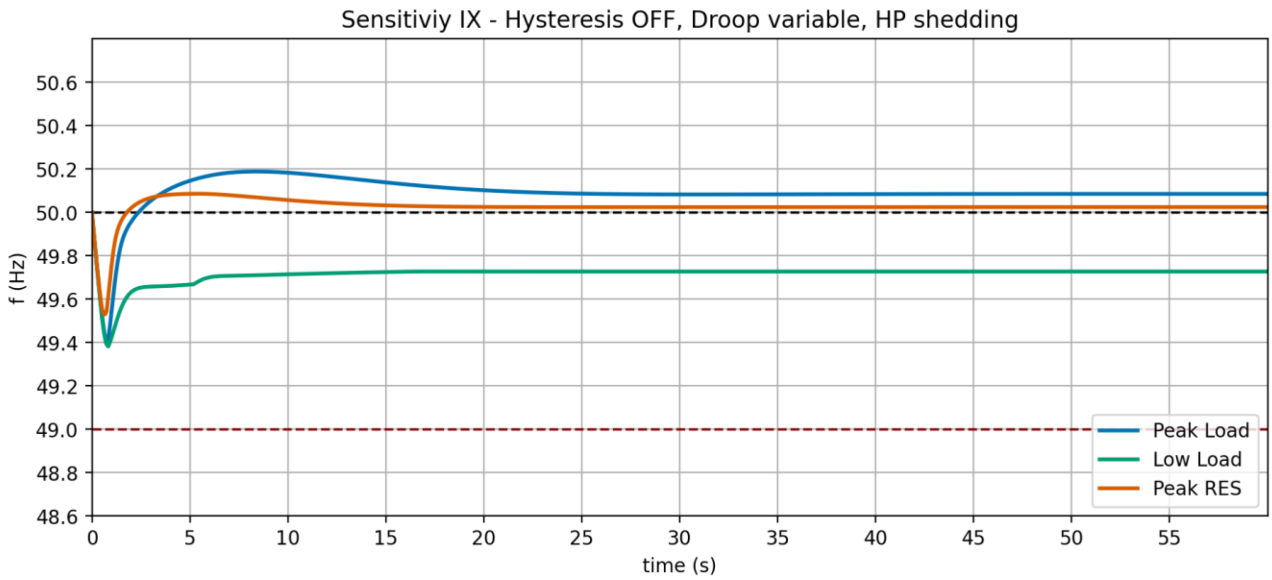

Figure 10: S-IX sensitivity (NT2040)

Smaller imbalances (below those that cause 1 Hz/s RoCoF) were simulated for S-IX as well to check for over-shedding. Also here, the system shows a robust behaviour at the investigated 3 GW (Figure 11), 8 GW and 13 GW (Figure 12) on both timeframes (2030 and 2040).

Moreover, it was tested that S-IX also works stable with more, less or no *Heat Pumps* available. Also in those cases, this sensitivity shows robust behaviour on both timeframes. If no *Heat Pumps* are available, again conventional load shedding is activated. On the 2030 timeframe, even twice the amount of *Heat Pumps* that were investigated before, did not show an overfrequencies exceeding 50.2 Hz and indicated a stable system response.

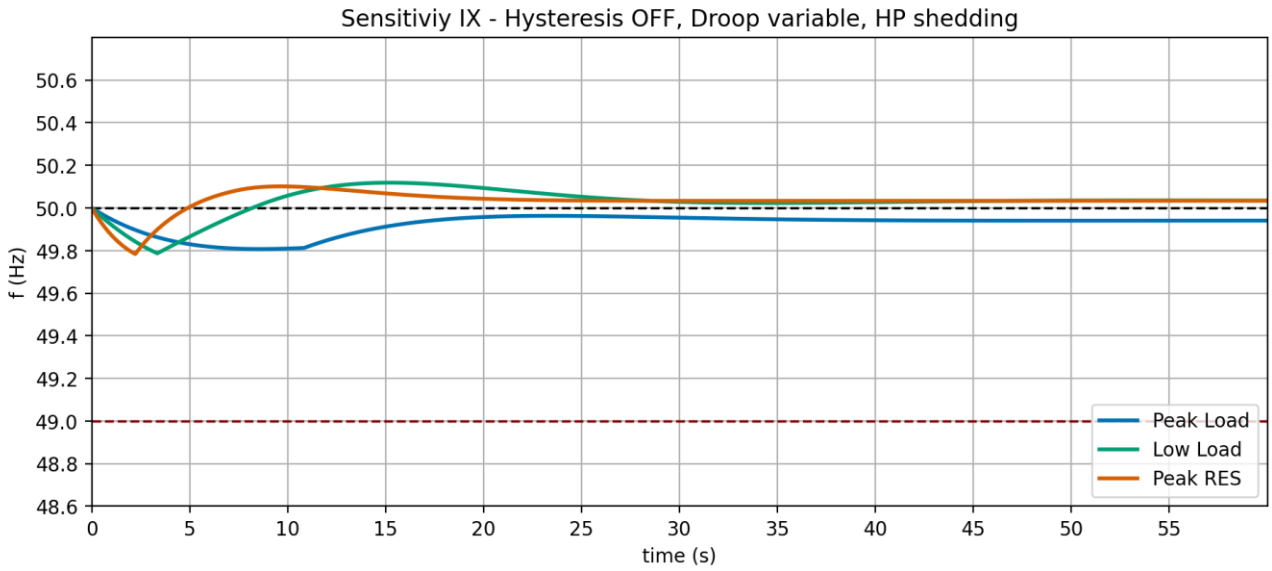

Figure 11: S-IX in NT2030 with small imbalance (3 GW)

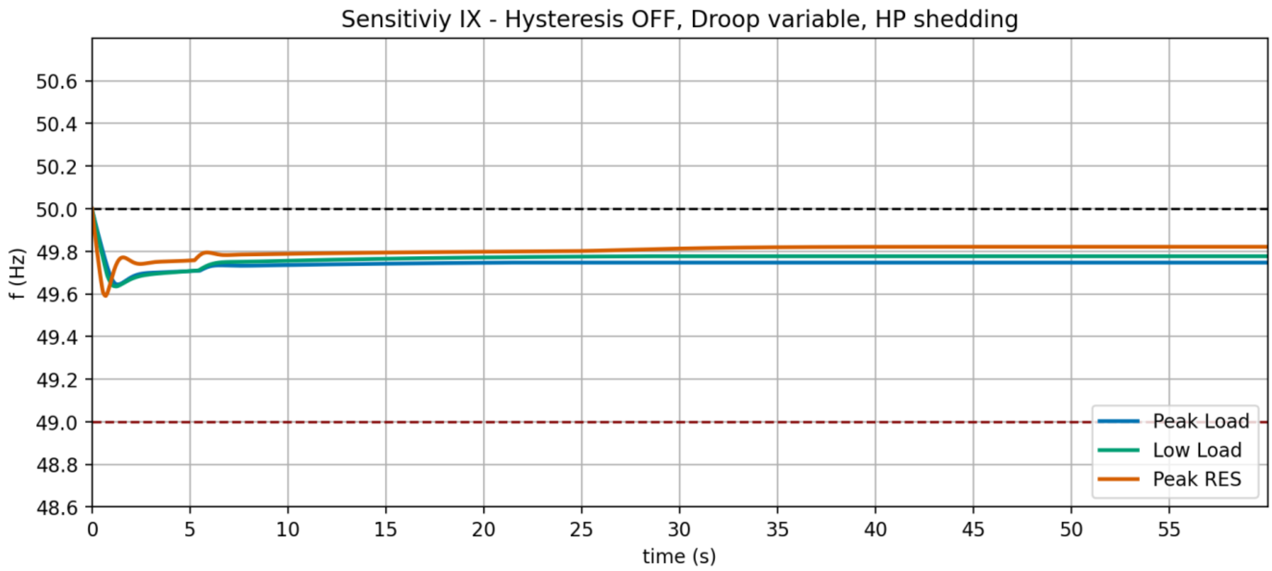

Figure 12: S-IX in NT2040 with 13 GW imbalance

Discussions and Uncertainties

This paragraph shall raise again the underlying uncertainties of this study that shall be taken into account in the subsequent discussions of the proposed recommendations. If reasonable, SPD will revise and update the simulations and recommendations based on new inputs from vendors and scenario data. Hence, the report presents a status-quo based on current knowledge about the technical capabilities of the different flexibilities and future scenarios.

Scenarios:
It is obvious that the installed capacity of each investigated flexibility influences the results significantly. Especially in the case of *Heat Pumps*, much higher amounts of installed capacities, compared to those that were investigated in this report (in 2030 and 2040 timeframes), may lead to adverse system behavior. A much larger amount of *Heat Pumps* that contribute to load shedding in the range of 49.6 Hz to 49.1 Hz could lead to over-shedding and subsequent over-frequencies in certain situations and hence trigger unwanted subsequent system reactions (e.g., large amount of non-compliant RES disconnection). It is therefore necessary to possibly update these recommendations based on new scenario data in subsequent network code revisions (e.g., RfG/DCC 3.0), if capacities diverge significantly from the current assumptions.

Load Shedding of *Heat Pumps*:
As indicated before, currently it is considered that *Heat Pumps* cannot adapt their active power fast enough to effectively perform LFSM-UC due to their technical constraints. If this assumption is challenged by the emergence of new technologies, LFSM-UC of *Heat Pumps* is the preferable choice. Especially for large industrial *Heat Pumps* (e.g., above a certain size of installed capacity or voltage level to be defined by the TSO), it will be favourable from the TSO perspective to not disconnect them completely at one frequency threshold (uncontrolled behavior), but to rather perform LFSM-UC. To ensure a level playing field for vendors in whole CE, the threshold that is “to be defined by the TSO” should ideally be aligned and uniform for all CE TSOs. This threshold will be worked out at a later stage.

Frequency Measurement of *Heat Pumps*:
Accurate and reliable frequency measurement and fast disconnection are no trivial tasks. In this study it is assumed that these tasks can be performed by *Heat Pumps* within 300 ms, even on the low voltage levels, where power quality is much lower than in TSO grids (voltage sags and disturbances, harmonic distortion etc.) and frequency measurement may take longer. If the assumption of 300 ms total disconnection time turns out to be infeasible and only much longer disconnection times (e.g., > 400 ms) of *Heat Pumps* are achievable, this can threaten a proper system response. Because then *Heat Pumps* could start to interfere with the conventional load shedding scheme and again may lead to over-frequencies due to over-shedding. This problem becomes worse with increasing RoCoFs. Hence, it will have to be confirmed that the control of *Heat Pumps* (and also the other flexibilities) is possible based on corresponding precise frequency measurements with 10…30 mHz accuracy and a total disconnection time of 300 ms.

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