European Network of
Transmission System Operators
for Electricity

Limited frequency sensitive mode

ENTSO-E guidance document for national implementation for network codes on grid connection

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DESCRIPTION

Code(s) & Article(s)	• Limited frequency sensitive mode – overfrequency (LFSM-O):
	  ○ NC RfG – Article 13(2)
	
	• Limited frequency sensitive mode – underfrequency (LFSM-U):
	  ○ NC RfG – Article 15(2)(c)

Introduction	The objective of this guidance document is to help to determine the main criteria/motivation for the specifications of the limited frequency sensitive mode capabilities of power generating modules at national level. Limited frequency sensitive mode at overfrequency (LFSM-O) is to be activated, when the system is in an emergency state of overfrequency and needs fast reduction of active power production. Consequently, all frequency containment reserves (FCR) in negative direction have already been deployed. Limited frequency sensitive mode at underfrequency (LFSM-U) is to be activated, when the system is in an emergency state after of underfrequency and needs fast increase in active power production. Consequently, all frequency containment reserves (FCR) in positive direction have already been deployed. For adequate specifications of the relevant parameters it is essential to be aware of the objective of the LFSM-O/-U functions and to understand how it interacts with other frequency stability requirements and assumptions for a system defence plan. In order to implement comprehensively the LFSM-O/-U capabilities this implementation guidance may go beyond the explicit requests of NC RfG and will also make recommendations on further parameters, which are not addressed in this network code, but are nonetheless relevant to ensure an adequate performance of these features. For each synchronous area, proposals for national choices for the non-exhaustive LFSM-O/-U parameters are provided through this IGD.
NC frame	The non-exhaustive topics are those for which the European level CNCs do not contain all the information or parameters necessary to apply the requirements immediately. These requirements are typically described in the CNC as “TSO / relevant system operator shall define” or “defined by / determined by / in coordination with the TSO / relevant TSO”. Despite choices need to be made at national level, frequency-related issues normally require a consistent response within the same synchronous area and therefore collaboration between TSOs of the same synchronous area is necessary. See also the general IGD on parameters related to frequency stability.

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Further info	IGD on parameters related to frequency stability IGD on frequency ranges IGD on frequency sensitive mode (FSM) IGD on admissible power reduction at low frequencies

INTERDEPENDENCIES

Between the CNCs	Response to frequency variations requires a coordinated response from all parts of a synchronous network and all users who provide frequency response. Therefore, there must be a coordinated frequency response across the network extending to not only the different interconnected countries, but across the interconnected network within the country i.e. DSOs, CDSOs and the users themselves. Also, there must be collaboration between all of these parties as we move typically from: • an early response (i.e. FSM, DSR SFC) even to small frequency variation to, • a response (i.e. LFSM, APC) to larger frequency variation, and; • finally a last response (LFDD) as last response to avoid network collapse
In other NCs	There is a link to the implementation of the network code on electricity emergency and restoration (Articles 15 and 16) applying the LFSM-O/-U capabilities in system operation. Consistency needs to be maintained here, i.e. it needs to be ensured that national connection code LFSM-O/-U capabilities are actually defined so that the settings that need to be applied can be developed through this operational network code.
System character-istics	System frequency typically deviates from its nominal value in case of imbalances between load and generation. Such deviation occur under normal operating conditions as a result of a mismatch between the actual system load and load forecasts, on which dispatchable generation is scheduled. Another source of load imbalance is the loss of generation or demand due to a failure in the customer installation or the network. System frequency increases in case of a generation surplus and decreases in case of lack of generation / demand surplus, because of an acceleration or deceleration of the rotating masses of synchronously connected generators. In order to cope with and compensate such frequency deviations frequency containment reserves (FCR) are deployed by generators running in frequency sensitive (FSM) mode (according to NC RfG type C and D power generating modules shall be capable of providing of FCR). Within a synchronous area FCR is dimensioned to keep the system frequency within a defined operational range based on a reference incident. For example, the relevant design criteria for the Continental Europe (CE) synchronous area is to keep the system frequency within 50.0 Hz ±200 mHz in case of a load imbalance of ±3.000 MW. Nonetheless more severe disturbances exceeding this FSM reference incident cannot be excluded and may occur in particular, if an interconnected system splits into separate parts each with a high load imbalance due to a high power exchange between these parts before the disturbance. In such cases frequency deviations larger than 50.0 Hz +/- 200 mHz with a high rate of change of frequency can be expected. LFSM-O is to be activated, when the system is in an emergency state after a severe disturbance, which has resulted in a major generation surplus and the frequency deviation cannot be mitigated by the FCR resources only. In such cases FCR resources are fully deployed, but system frequency cannot be stabilized and increases further. The slow

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activation of FCR resources (due to high RoCoF) can also contribute to high frequencies. The active power decrease of all power generation modules according the LFSM-O specifications shall support stabilizing the system at a frequency < 51.5 Hz after FCR has been exhaustively deployed to avoid a system collapse and gain time for further operational measures for frequency reduction. In case of LFSM-O activation and increasing frequency power generating modules shall continuously decrease the active power towards the minimum regulating level according to the selected droop. For type A generators the TSO may allow alternatively that such behaviour is emulated by disconnection at randomised frequencies.

LFSM-U is to be activated, when the system is in an emergency state after a severe disturbance, which has resulted in a major generation shortfall and the frequency deviation cannot be mitigated by the FCR resources only. In such cases FCR resources are fully deployed, but system frequency cannot be stabilized and decreases further. The slow activation of FCR resources (due to high RoCoF) can also contribute to low frequencies. The active power increase of all power generation modules type C and D according the LFSM-U specifications shall support stabilizing the system at a frequency > 49.0 Hz after FCR has been exhaustively deployed and before load shedding is activated. In case of LFSM-U activation and decreasing frequency the power generating modules shall continuously increase the active power towards to the highest achievable output (taking into account a reduced maximum capacity at low frequencies, if applicable) at that moment according to the selected droop.

The rate of change of frequency (RoCoF) and the magnitude of the deviation due to a load imbalance are highly dependent on the transient dynamic behaviour of the interconnected system in case of loss of either generation or demand. This transient behaviour is determined by the system inertia, which is typically lower for small synchronous areas with typically a higher share of non-synchronous generation to total generation in operation, such as for Ireland or GB, where a single loss of a generator or HVDC interconnector can result in a change in system frequency that is markedly greater than what could be in CE synchronous area. However, since a CE system split – as occurred last in November 2006 – is a reasonable design case to be taken into account, large transients in frequency need to be withstood and mitigated there as well. Furthermore, system inertia tends to continuously decrease with increasing instantaneous penetration of renewable energy sources (RES) due to the progressing displacement of synchronous generators by non-synchronously connected power park modules.

This leads naturally to the need for a faster and/or larger response in future to arrest a change in frequency and restore the nominal frequency. It is therefore evident, that response time is a crucial factor of the LFSM-O/-U performance.

Frequency sensitivity increases at low system inertia and power generating modules will be needed more to support frequency. It is therefore increasingly relevant to have the capability to adequately respond in such situations. State-of-the-art inverters to connect most of the renewable production are fully controllable sources. Setting their operational parameters correctly contributes essentially to secure system operation within the operational limits.

Technology characteristics

By principle, LFSM-O service can be provided by every power generating module in operation above its minimum regulating level. As it is to be understood as a minimum active power reduction at a specific (high) frequency any further reduction at this frequency, may it be due to a shortfall of the primary energy (e.g. wind) or due to network constraints is

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harmless, but would even support the effect of LFSM-O.
In contrast, the provision of LFSM-U service may be subject to further preconditions. An active power increase is possible only for generators running below their maximum capacity. Typically RES generation however is dispatched according to their maximum available primary energy, unless there are network constraints. LFSM-U capability shall not be understood as requiring power generating modules to run at a reduced active power output just to be prepared for an increase in case of an unlikely low frequency event. The economic generation dispatch hence shall not be limited by LFSM-U performance.

With regard to network constraints at distribution level, which typically require a network operator to instruct the power generating facility operator to reduce the active power output to avoid overloading and line tripping, this could be contradictory to a LFSM-U request. Therefore there is a need for defining the ranking of LFSM-U and local network constraint management measures. The benefit to the wider society by possibly avoiding wide-spread load shedding or even a system collapse by LFSM-U performance needs to be weighed against safeguarding a local/regional network tripping. Moreover, in a larger synchronous area a simultaneous local constraint and a wider system LFSM-U event is quite unlikely. Given these considerations, priority of the local constraint management over the LFSM-U performance can be granted by allowing the Relevant Network Operator to block the LFSM-U function given that:

- LFSM-U blocking is activated only in case of network constraints observed in real time and not based on forecasts of possible constraints.
- LFSM-U blocking is strictly limited to the constrained part of the network.
- The Relevant Network Operator shall provide the TSO control room with a signal identifying the scale of LFSM-U blocking activated within its network in real-time

Concerning the LFSM-O/-U capabilities NC RfG requires to define at national level:

- Frequency threshold of LFSM-O/-U activation
- Droop settings to determine the sensitivity of a change in active power to change in frequency

Due to the system-wide effect of frequency-related issues, a harmonised setting of these parameters within a synchronous area is essential. Otherwise adverse impacts can occur, which may aggravate the emergency situations, in which LFSM-O/-U is activated. Diverging frequency thresholds between control blocks may result in unwanted load flow patterns, if in one control block generators already change active power output while generators in another control still remain “silent”. A comparable effect may occur in case of diverging droop settings. Hence it is recommended to align these parameters at synchronous area level.

In order to best coordinate active power response by LFSM-O/-U with the provision of FCR, it is recommended to activate it at full deployment of FCR, i.e. to set the frequency threshold such, that there is no overlap or gap between FCR and LFSM-O/-U. Hence, the following frequency threshold are recommended for each synchronous area:

Synchronous area	LFSM-U threshold	LFSM-O threshold
Continental Europe	49.8 Hz	50.2 Hz
Nordic	49.5 Hz	50.5 Hz
Great Britain	49.5 Hz	50.5 Hz
Ireland	49.5 Hz	50.2 Hz

Baltic	49.8 Hz	50.2 Hz

Table 1: LFSM-O/-U activation thresholds per synchronous area

Concerning the droop settings, it is recommended to keep an adjustable range of 2% - 12% for both LFSM-O/-U. From the perspective of a technical capability with relevance to plant design it is important to take care and emphasize in the national implementation, that the plant control systems indeed allow adjusting and reselecting the droop setting over the plant's lifecycle. An ENTSO-E survey on technical capabilities for frequency stability has shown, that an adjustable droop is technically feasible not a significant cost issue for plant design. However, a very low droop setting with more frequency sensitive responses could lead to increased maintenance costs. Taking into consideration these aspects and the fact, that an overfrequency emergency situation requires a clear-cut active power response since active power reduction is the only countermeasure against high frequency, the proposed default droop settings are:

Synchronous area	LFSM-O default droop settings of PGMs
Continental Europe	5%
Nordic	4%
Great Britain	2-10%
Ireland	4%
Baltic	5%

Table 2: LFSM-O default droop settings per synchronous area

When setting the LFSM-U droop, it should be considered, that LFSM-U may be less effective, because less generators will be able to contribute as explained above and finally load shedding provides another countermeasure. Hence, no definite recommendation for LFSM-U droop is given, because it needs to be assessed based on assumptions on volume of generators to participate. Being part of emergency control it needs to carefully coordinated and aligned with the other defense plans measures to mitigate low frequency events, e.g. LFDD.

According to NC RfG, the LFSM-O/-U droop is defined as

$$s[\%] = 100 \cdot \frac{|\Delta f| - |\Delta f_1|}{f_n} \cdot \frac{P_{ref}}{|\Delta P|}$$

P_{ref} is the reference active power to which ΔP is related and may be specified differently for synchronous power generating modules and power park modules. ΔP is the change in active power output from the power-generating module. f_n is the nominal frequency (50 Hz) in the network, Δf is the frequency deviation in the network and Δf_1 is the frequency threshold of the LFSM-O/-U. At overfrequencies/underfrequencies where Δf is above/below Δf_1, the power generating module has to provide an active power output change according to the droop.

NC RfG allows for two options for defining P_{ref} for power park modules, either P_{max} or the actual active power output at the moment the LFSM threshold is reached. It is recommended to select P_{max} as a reference for power park modules, which are typically operated at or near maximum capacity. For those power park modules, which are operated at partial load most of the time the preferable reference is the actual active power output at the moment the

LFSM threshold is reached. This choice would enable at system level an equitable active power response to a high or low frequency event regardless of the number of power generating modules in operation.

From the system transient behaviour and for successful LFSM-O/-U performance it is essential to define the response time of LFSM-O/-U activation. Therefore this IGD recommends the relevant settings even though they are not addressed by NC RfG.

The duration of a response to reach a set value is defined by the response time. The response time (T_{resp}) is defined as the time from the step inception (e.g. a step in frequency) until the response (e.g. change of active power) reaches the tolerance range of its set value first. It includes an initial delay (T_{id}), which covers the period between step inception and the beginning of the response.
The tolerance range defines the range around the set value as describe figure 1. The recommended tolerance range is in:

- small synchronous areas: ±2% (Nordic, GB, IE, Baltic)
- large synchronous area: ±5% (CE)

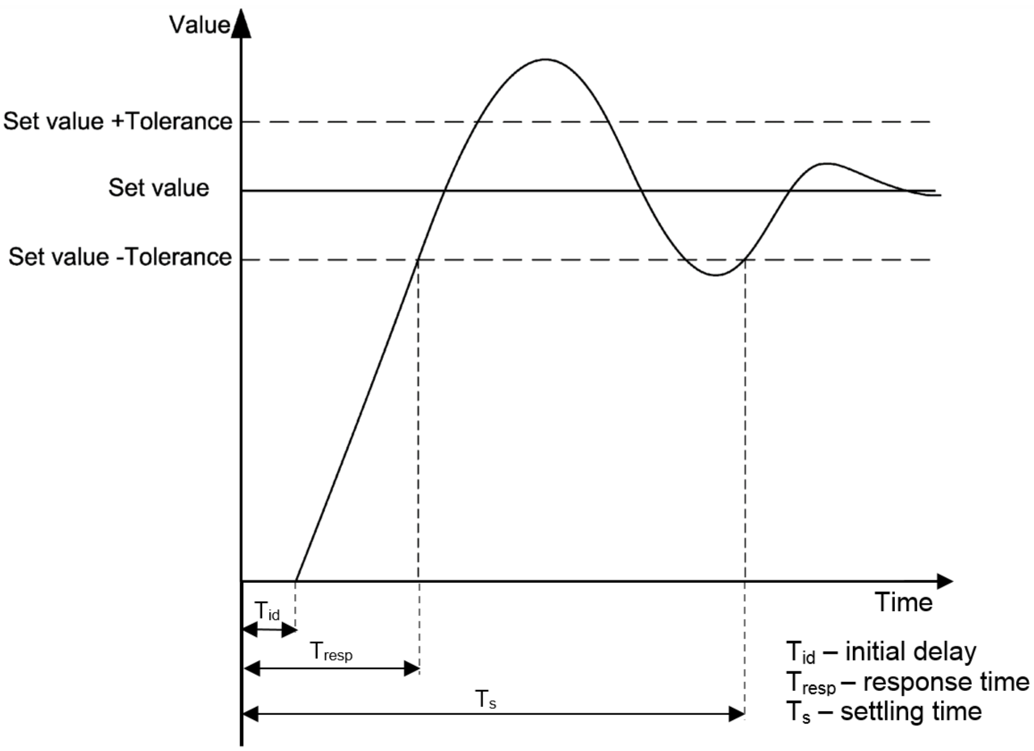

Figure 1: Definition of response parameters

The response time depends on the power generating module technology. Synchronous power generating modules are able to provide inertia, but on the other hand are typically not able to adapt power output very fast. Power park modules have no or just very little inherent inertial response, but are typically able to swiftly adapt their power output. Taking these characteristics into consideration it is recommended to distinguish between these types of power generating modules. Moreover, further constraints may apply to certain technologies and need to be taken duly into account.

The recommended response times for active power increase in case of decreasing frequency are:

- Synchronous power generating modules: ≤ 5 min for an active power change of 20% maximum power (slow performance not applicable, if the increase follows shortly (within a few seconds) after the decrease)
- Power park modules (except for wind generators): ≤ 10 s for an active power change of 50% maximum power
- Power park modules (wind generators): ≤ 5 s for an active power change of 20% maximum power, if the current active power is above 50% of maximum power. At operating points below 50% of maximum power a slower reaction may apply, because the wind generator response is limited by the kinetic energy of rotating masses. Nonetheless, the response time shall be as fast as technically feasible and justified to the relevant network operator if > 5s.

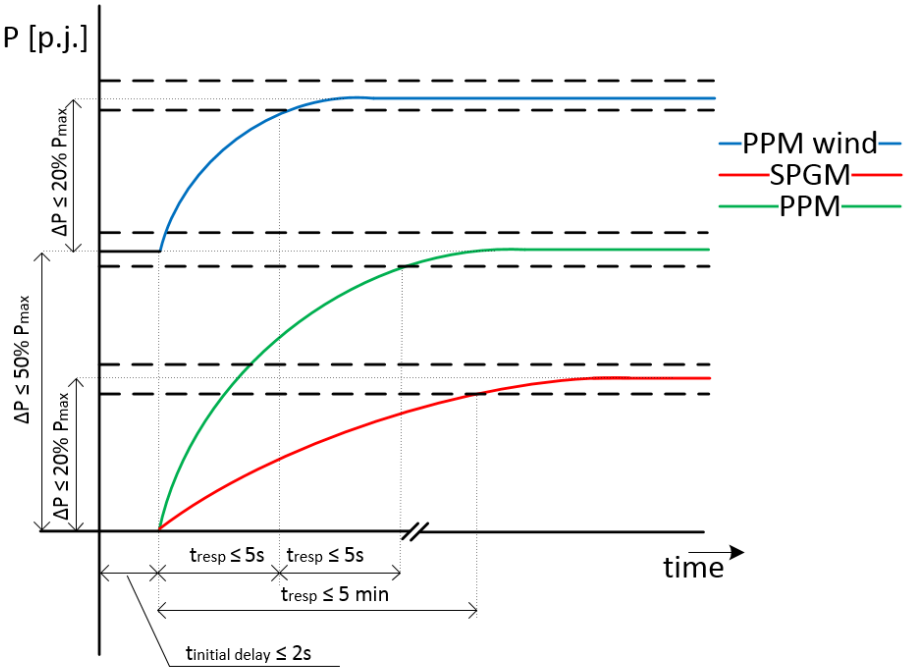

Figure 2: Response time in the direction of active power increase

The recommended response times for active power decrease in case of increasing frequency are:

- Synchronous power generating modules: ≤ 8 s for an active power change of 45% maximum power
- Power park modules: ≤ 2 s for an active power change of 50% maximum power

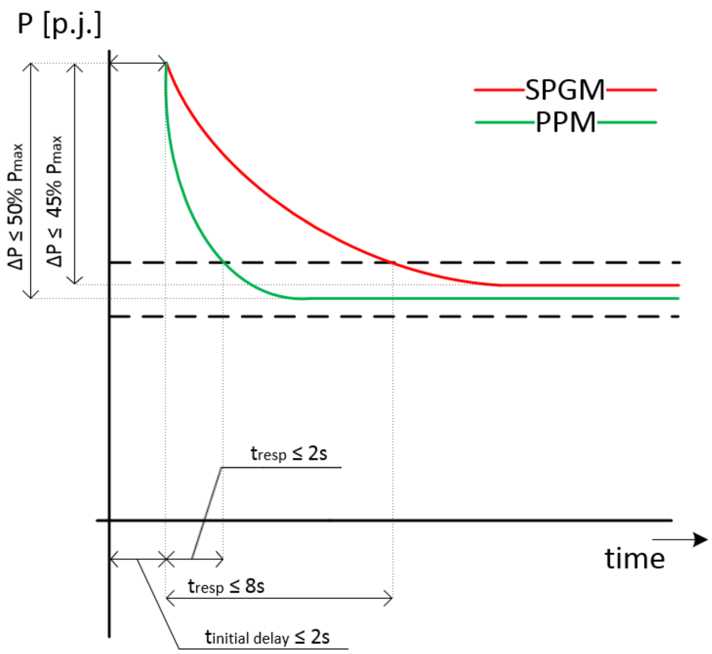

Figure 3: Response time in the direction of active power decrease

If the active power change is greater than the given limits, the response time for the part of the active power change exceeding the given limit shall be as fast as possible. It applies to both directions (increase or decrease of active power output).

The recommended response time values consider technical constraints power generating modules technologies. According to wind turbines manufacturers the wind turbines are able to achieve response times of 5 s for an active power increase of 20% maximum power (see above). The response time depends largely on the actual active power operating point (higher production = shorter response time), ambient conditions (higher wind speed = shorter response time) and type of turbines (large diameter of turbine = longer time response). Wind turbines are less controllable below 10% of maximum power (because of mechanical constraints in the gearbox). The response of thermal power generating modules is determined by the maximum ramp to change active power output. Maximum step response time could also be limited by emission compliance. Time response is limited by slow reaction of conventional boilers in sliding pressure mode (inherent feature).

It needs to be emphasized, that extensive dynamic studies have been performed on frequency stability criteria and ENTSO-E has respective reports for the Continental Europe synchronous ([1], [2]). These reports clearly conclude that in future LFSM-O response times of 1s are required to withstand severe disturbance like a system split similar to the event of 4. November 2006, when Continental Europe split into three parts. The diagram below shows, that the system frequency would otherwise exceed the threshold of 51.5 Hz, at which power generating modules are allowed to disconnect.

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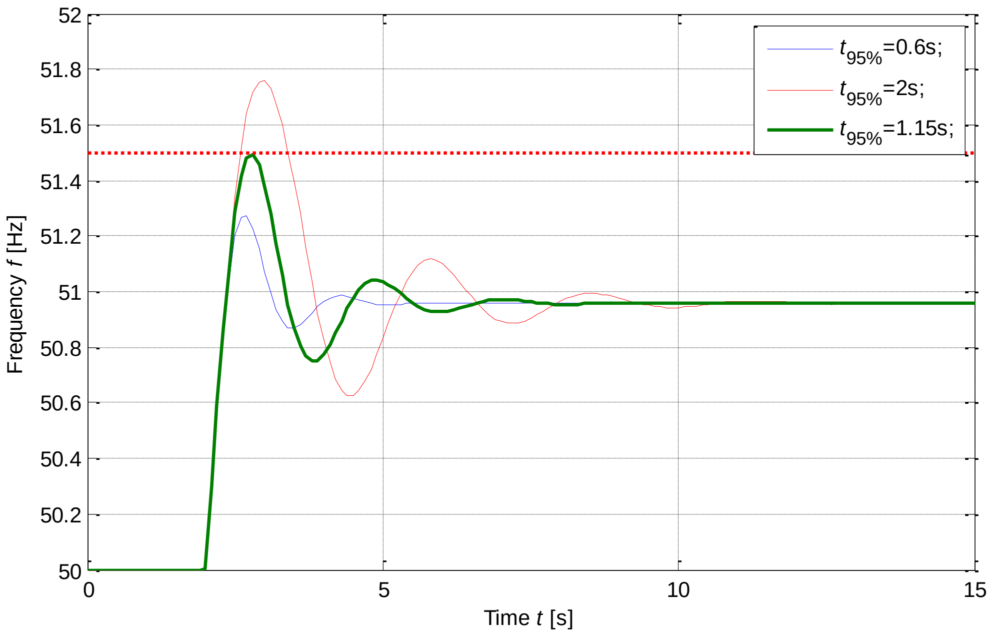

Figure 4: System frequency response to a CE system split event [1]

Furthermore, the simulations of a large number of fault scenarios for Continental Europe reveal, that the percentage of successfully withstood scenarios decreases significantly with slower response times. The diagram below shows the impact of response time, frequency threshold of LFSM-O activation and droop settings on the capability to withstand fault scenarios.

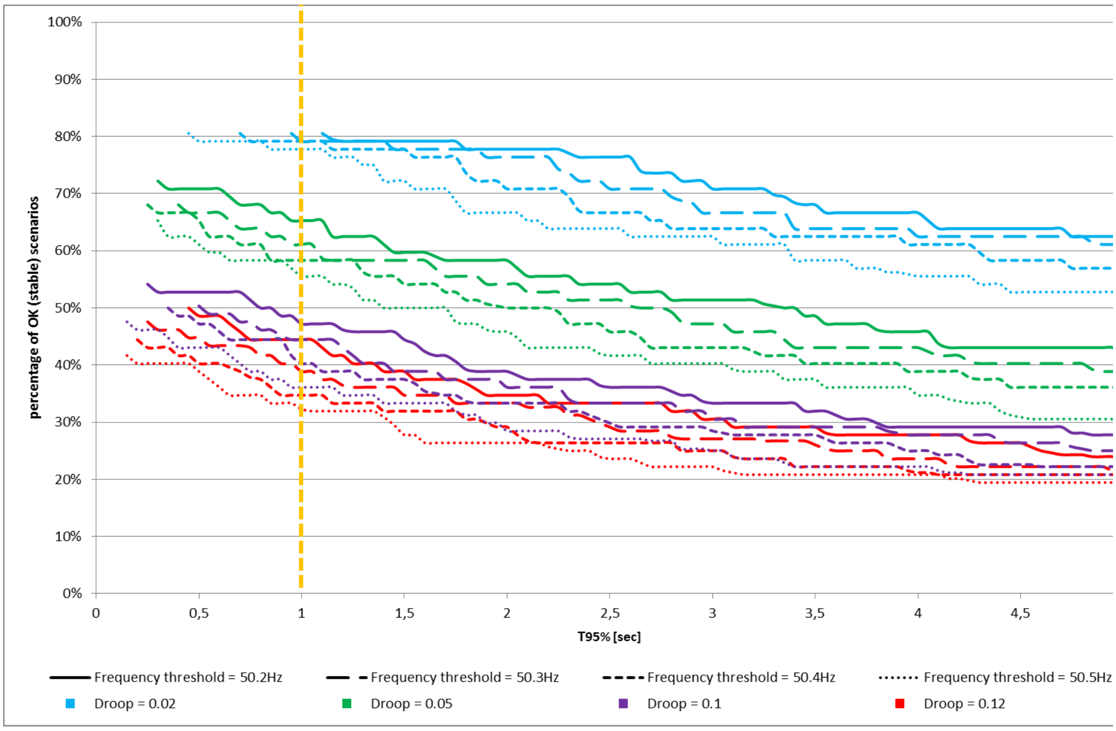

Figure 5: Percentage of CE fault scenarios, which can be stably withstood as a function of LFSM-O activation threshold and droop setting

The recommendations on response times clearly take into consideration what generation technology can deliver today and in the near future and are evidently less stringent than what would be needed from a system engineering perspective. To close this gap, best efforts are needed in technology development to lower the technically feasible response times. To achieve the fastest technically feasible response times, the inherent dead time between the triggering events and the start of the response needs to be as short as possible and any intentional delay shall be prohibited.

The settling time defines the period for stabilizing the response within the tolerance range of the set value. It is defined from step inception to the point in time from which on the response does not exceed the tolerance range anymore. The settling time shall be set according to the technical capabilities of power generating modules and system needs. Therefore the settling times for synchronous power generating modules and power park modules are defined separately and a distinction is made between active power increase and decrease. Recommended values are:

- active power decrease in case of increasing frequency during LFSM-O/-U activation:
  - synchronous power generating modules: ≤ 30 s
  - power park modules: ≤ 20 s
- active power increase in case of decreasing frequency during LFSM-O/-U activation:
  - synchronous power generating modules: ≤ 6 min (slow performance not applicable, if the increase follows shortly (within a few seconds) after the decrease)
  - power park modules: ≤ 30 s

The settling time generally depends on the power generating module technology. The settling time of synchronous power generating modules (rotating electrical machines) are characterized by their inherent capabilities (friction of rotating parts, electromagnetic force between rotor and stator, electromechanical transients, …). The generators are on the same shaft as the prime mover, therefore the total gen-set inertia is also impacted by the prime mover. The settling times of power park modules are determined by inverter settings and additionally other facilities (flywheels, batteries, …) at the connection point need to be considered. Other power park modules such as wind farms are asynchronously rotating machines with a settling time of tenths of seconds (20 seconds for decrease of active power or 30 seconds for increase of active power).

COLLABORATION

TSO – TSO LFSM-O/-U setting shall by coordinated at synchronous area level. The motivation is to enable coordinated measures against extreme frequency deviations. The frequency threshold and droop shall be explicitly coordinated among countries of the same synchronous area.

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TSO – DSO	LFSM is activated automatically. In particular an increase of active power could cause a overloading of lines in radial distribution networks. Therefore it considered necessary to collaborate between TSOs and DSOs on priorities of LFSM-U operation against local constraints management. In particular, conditions of eventual LFSM blocking need to be agreed between the network operators.
RSO – Grid User	The parameter settings and the relevant rationales behind shall be presented to power generating facility owners. It shall aim at better mutual understanding of system needs vs. technical limitations of power generating modules, of which the response time of a change in active power output is likely the most critical aspect, because of the risk of a gap between system needs and technical capabilities. New power generating modules shall be capable of activating LFSM according to the recommended ranges to establish an equitable response to frequency excursions across a synchronous area.

Abbreviations			
APC	Active Power Control	**LFDD**	Low Frequency Demand Disconnection
CDSO	Closed Distribution System Operator	**LFSM**	Limited Frequency Sensitivity Mode
CDS	Closed Distribution System	**PGFO**	Power Generating Facility Owner
DCC	Demand Connection Code	**PGM**	Power Generating Module
DF	Demand Facility	**PPM**	Power Park Module
DR	Demand Response	**RfG**	Requirements for Generators
DU	Demand Unit	**ROCOF**	Rate Of Change Of Frequency
DSO	Distribution System Operator	**RPC**	Reactive Power Control
FSM	Frequency Sensitivity Mode	**RSO**	Relevant System Operator
HVDC	High Voltage Direct Current	**SFC**	System Frequency Control
IGD	Implementation Guidance Document	**TSO**	Transmission System Operator
SPGM	Synchronous Power Generating Module		

Reference

[1] Frequency Stability Evaluation Criteria for the Synchronous Zone of Continental Europe, RG-CE System Protection & Dynamics Sub Group, March 2016. Link: https://www.entsoe.eu/Documents/SOC%20documents/RGCE_SPD_frequency_stability_criteria_v10.pdf

[2] DISPERSED GENERATION IMPACT ON CE REGION SECURITY, DYNAMIC STUDY 2014 REPORT UPDATE, 11-12-2014. Link: https://www.entsoe.eu/Documents/Publications/SOC/Continental_Europe/141113_Dispersed_Generation_Impact_on_Continental_Europe_Region_Security.pdf

[3] TECHNICAL BACKGROUND AND RECOMMENDATIONS FOR DEFENCE PLANS IN THE CONTINENTAL EUROPE SYNCHRONOUS AREA, SYSTEM PROTECTION AND DYNAMICS-REGIONAL GROUP CONTINENTAL EUROPE, 26.10.2010. Link: https://www.entsoe.eu/fileadmin/user_upload/_library/publications/entsoe/RG_SOC_CE/RG_CE_ENTSO-E_Defence_Plan_final_2011_public.pdf

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