European Network of
Transmission System Operators
for Electricity

Maximum Admissible Active Power Reduction at Low Frequencies

ENTSO-E guidance document for national implementation of conditions for maximum admissible active power reduction at low frequencies

Revised Clean Version | 12 April 2021

Prepared from: StG CNC

TABLE OF CONTENTS

Description

Introduction

The objective of this implementation guidance document (IGD) is to advice on the national level specification of the capability of power generating models (PGMs) to avoid the reduction of active power output more than an admissible value due to the decrease of frequency following a disturbance.

For the national implementation of the relevant parameters it is essential to emphasise the objective of this requirement and to clarify how it interacts with other frequency stability requirements and external factors such as power plant technology and ambient conditions.

For each synchronous area, proposals for national choices of the non-exhaustive requirement on admissible active power reduction at low frequencies are provided through this IGD.

NC frame

The non-exhaustive requirements are those for which the European level connection network codes (CNCs) do not contain all the information or all parameters which are necessary to implement 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". More about non-exhaustive requirements could be found in the IGD on Parameters of Non-Exhaustive Requirements.

Regardless of choices that need to be made at national level for this requirement, the frequency-related issues normally require an equitable system-wide response and therefore the collaboration between transmission system operators (TSOs) at synchronous area.

The implementation of article 13 (4) of the NC RfG shall establish at least a $P_{max}(f)$-characteristic which falls within the acceptable range defined by the NC RfG. Article 13(5), complementing Article 13(4) clarifies that ambient conditions, for which the characteristics are defined. These characteristics shall be given clearly as these have an important influence on the capability of power generating modules to comply with the requirement. Furthermore, Article 13(5) draws specific attention to the fact that some technologies are very sensitive to the value chosen when specifying this requirement. It could make sense to harmonize ambient conditions at ENTSO-E level and maybe further with existing standards.

For some technologies the compliance with the most onerous possible specification of the requirement may be challenging. Furthermore, system needs also highly depend on the time domain (transient or steady-state) for which the requirement is defined. Both of these aspects would lead to the definition of multiple $P_{max}(f)$-characteristics for different time domains.

Harmonization of the requirement at synchronous area level is needed, especially for the system dynamics driven part of the requirement (transient/dynamic time domain). Harmonization of the technology dependent part of the requirement (steady-state time domain) at synchronous area level would be beneficial to support a level playing field for all grid users.

Finally, the harmonization of the requirement at ENTSO-E, even if numerical values differ for each synchronous area, should be reached in order to facilitate harmonised technology development and compliance verification as well as comparison and monitoring of the network code implementation.

Further information

Beside the present implementation document, the reader could follow the following implementation guidance documents as given below:

- IGD on parameters related to frequency stability
- IGD on frequency ranges
- IGD on RoCoF
- IGD on FSM

Interdependencies

Between the CNCs

The implementation of the requirement of Articles 13 (4) and 13 (5) is strongly linked to other frequency parameters in the connection network codes (CNCs), especially to rate of change of frequency (RoCoF), frequency sensitive model (FSM) and frequency range withstand capabilities.

In other CNCs

The characteristic nationally defined for this requirement has a strong impact on the sizing of synchronous area frequency containment reserves (FCR), frequency restoration reserves (FRR) and low frequency demand disconnection (LFDD) schemes as defined in the System Operation Guidelines[1] (SOGL) and the network code on emergency restoration (NC ER)[2].

System characteristics

A system frequency drop is always linked to a power imbalance between generation and demand in the synchronous area. In order to support the frequency stability and to not impair the system dynamic response, it is important that at low frequencies occurring during power imbalances that

1 COMMISSION REGULATION (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation
2 COMMISSION REGULATION (EU) 2017/2196 of 24 November 2017 establishing a network code on electricity emergency and restoration

the active power output of PGMs is reduced as little as technically possible from its pre-disturbance operating point. It is worth mentioning that disturbances leading to large signal frequency deviation (i.e. where in such disturbances the frequency deviates out of the 49,8-50,2 Hz band) is expected to be very rare (usually during system splits). Nevertheless, the consequence of not having a sufficient response from the running power generating units can be significant for the system frequency stability. This justifies the major importance of such requirement to ensure system security and stability.

Such continuous supportive response provided by the PGMs to the system is needed in different time frames. As mentioned above the exhaustive description of these time frames increases transparency and harmonized understanding of the requirement and aims at taking technology limitations into account while meeting system needs.

Frequency support is needed during the initial frequency transient (immediately after the power imbalance in the network occurs) and until frequency is stabilized. This process is addressed by the expected transient characteristics. This requirement allows the system to remain stable before activating the LFDD schemes for a normative incident (e.g. loss of 3 GW of generation for CE case). The frequency nadir during the frequency transient response shall not be lower than 49 Hz.

The time $\mathbf{t_1}$ of the frequency transient response is defined as the time at which the system could reach 49Hz after the disturbance. This is associated with the maximum expected RoCoF (Hz/s), for which the withstand capability is defined (see IGD on RoCoF). The time $\mathbf{t_2}$ of the transient behaviour is associated to the maximum time needed to stabilize the system frequency. This is typically linked to the full deployment time of the FCR. Figure 1 provides a schematic overview for the values **t1** and **t2**.

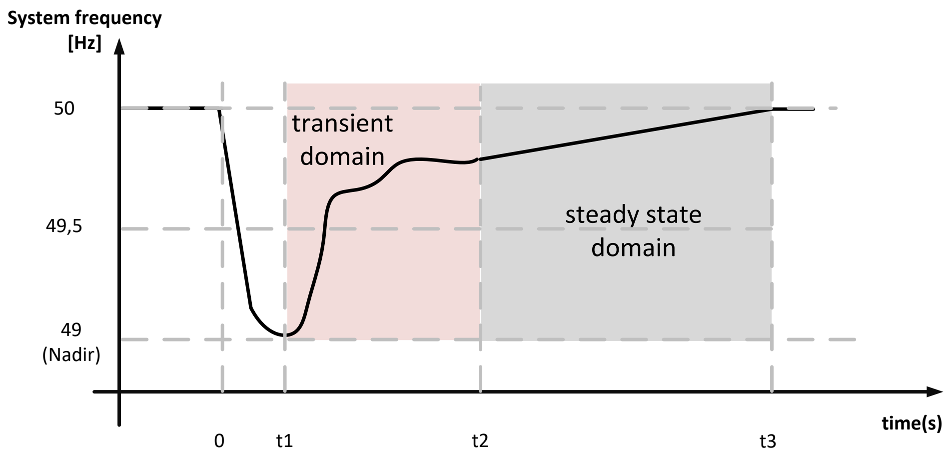

Figure 1. An illustrative representation of the frequency response under a large disturbance (out of the normative 3GW loss of generation) with purpose to define the variables t1, t2 and t3 used in this IGD. The frequency response profile presented in this figure is for the specific case that the frequency Nadir reaches 49Hz (without the activation of LFDD).

In addition, the required system support is needed also after frequency has been stabilized (time **t2**) and until the frequency is restored to a normal state (time **t3**). This is addressed by the expected **steady-state characteristics**. This requirement allows the slower automatic and manual action to be well sized and efficiently activated to restore a normal power system operating state.

The initial time of the steady state domain is aligned with the final time t_2 of the transient domain. The final time t_3 of the steady state domain is aligned with the expected minimum duration of the frequency withstand capability of the power plant as defined by national implementation of the NC RfG Article 13(1).

Any decrease of active power at low frequencies is detrimental to system security and therefore each PGM shall reduce it's active power output as little as technically feasible in such a situation. Therefore, **the requirement shall define the maximum admissible active power reduction at low frequencies but no intentional decrease of active power to align the NC requirement will be accepted**.

Power park modules (PPMs) and many typologies of Synchronous PGM (SPGMs) do not have specific technology limitation within the range defined in the NC for both Articles 13(4) and 13(1). Therefore, the maximum admissible active power reduction at low frequencies should be avoided. Taking into account the range defined by the NC, **no active power reduction is considered admissible above 49Hz for PPMs (the latter is both for the transient and for steady state domain as it will be explained in the following graphs)**. With regard to the capability of the PPMs to withstand RoCoF in the transient period, we recommend to follow the guidance of the IGD on RoCoF. Below 49Hz, the most stringent value in line with the CNCs would consider a maximum active power reduction of 2%/Hz to be admissible although it is not expected, as PPMs have no specific technology limitation within this range. This maximum admissible active power reduction at low frequencies would be required from a time t_1 after the beginning of the frequency transient and until time t_3 which is aligned with the minimum duration for frequency withstand capability of the power plant as defined by national implementation of the NC RfG article 13(1). Hence, for PPMs the same capability with regard to the maximum admissible active power reduction should be requested during the transient and steady state domain.

Time t_1 is linked to the time at which the system could reach 49Hz. This is therefore related to the maximum RoCoF which can be expected and linked to the defined withstand capability of PGMs. In line with the IGD on RoCoF where, for the normative incident a value of 2Hz/s could be expected, the recommended value for t_1 is then 0.5s.

No voluntary active power reduction is accepted if the PGM does not have inherent technology constraints, duly demonstrated by the PGM owner.

Based on technology-dependent limitations and on existing practices reflecting system needs, it is proposed to define two time domain characteristics as maximum admissible active power reduction at low frequencies, the **transient behaviour (transient characteristics)** and the **steady-state behaviour (steady-state characteristics)**:

1. Concerning the **transient characteristics**, the following points are recommended for the national implementation:
   a. **No active power reduction is considered admissible during the observed power system transients for the normative incident above the LFDD frequency threshold**. The main reason for imposing such requirement is to maintain the active power output of a PGM constant until the stage of LFDD is activated. More specifically:
      i. In the case of a significant amount of SPGM, the shortest duration time at which the system can reach 49Hz is expected to be 0.5s. This is in line with the IGD of RoCoF which recommends a withstand capability of 2Hz/s for SPGM, having for consequence that 49Hz could be reached after 0.5s for the normative incident. The desired system value for t_1 would then be 0.5s. However, taking into account current reaction and response limitations of SPGM technologies, **a value of $t_1 \leq 2s$ could be acceptable** in line with the time defined for similar facts in the context of frequency sensitive model (FSM) capabilities[3].
      ii. In the worst case incident <u>**not**</u> **leading to low frequency demand disconnection (LFDD)** (based on the ENTSO-E system protection and dynamic working group analysis and the existing national code requirements), **the value of t_2 equals to 30s for CE synchronous area**. For some synchronous areas this time could also be linked to the full deployment time of the FCR (e.g. 30s).
   b. **Below 49Hz, the active power reduction is admissible, because the LFDD will counteract to further frequency decrease**. The slope of the maximum admissible active power reduction at low frequencies should be designed to be less constraining than the LFDD equivalent slope (in order to keep a positive system balance). LFDD is typically designed to reach 45% of total load shed at 48Hz. **The upper slope (i.e. 2%/Hz) is therefore proposed in order not to jeopardise the efficiency of LFDD**.
   c. An illustration of the expected transient response is given in figure 2. As shown, for the case of the transient domain where the transient characteristics apply, active power reduction is not allowed above 49Hz (orange area). For all the frequency variations which are above the line (ab), the expected active power output of the PGM shall be kept constant. For a falling frequency below 49Hz, the active power response of the PGM should be above the line (BD). It is important to be noted that the figure 2 presents a linear falling frequency which could be associated to the RoCoF value in a SA.

[3] The initial activation of control actions needed to maintain active power output in case of frequency deviation shall not be unduly delayed. If the delay in initial activation of control actions needed to maintain active power output in case of frequency deviation is greater than two seconds, the power- generating facility owner shall provide technical evidence demonstrating why a longer time is needed.

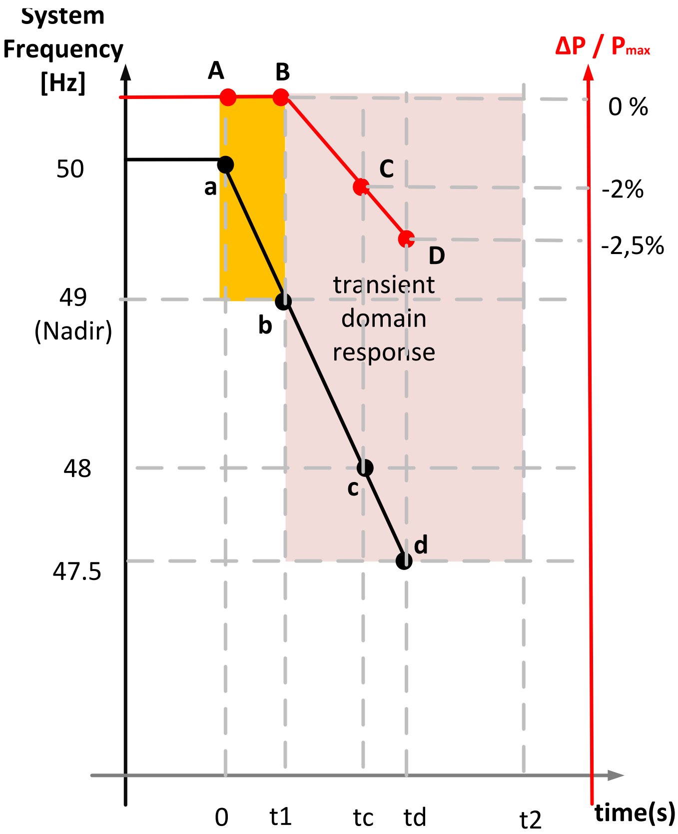

Figure 2. The maximum admissible active power reduction in the transient domain for the case of falling system frequency. The power slope of the maximum admissible active power reduction for this example is taken as 2%/Hz. With black the system frequency and with red the active power variation.

2. With regard to the **steady-state characteristics the following points are recommended for the national implementation:**

   a. **Concerning the steady-state domain**, it is proposed to request the active power performance until time **t3** (see also previous figure 1) which is aligned with the minimum duration for frequency withstand capability of the power plant as defined by national implementation of the NC RfG Article 13(1). However, in case of limited maximum admissible active power reduction in the steady state domain at low frequencies (e.g. 2%/Hz) some technologies, mainly combined cycle gas turbines (CCGT), have limitations which should be taken into account.

   b. Different requirements for the steady state domain per country could take place, but harmonized within a synchronous area (e.g. UK, IE = 2%/Hz, CE, Nordic & Baltic = 10%/Hz). However, for countries within the synchronous area which are exposed to a higher risk of islanding (e.g. peninsular area), a more stringent slope of the maximum admissible active power reduction at low frequencies could be defined at time of national implementation of the NC RfG Article 13(4) & 13(5). It must be noted that to facilitate the compliance of a PGM with transient and steady-state characteristics, the latter should be always less constraining than the first one. This is also in line with the system need for a stronger frequency support in case of transient conditions.

c. An illustration of the expected transient response is given in figure 3 for the steady state domain. As shown, active power reduction is not allowed above 49.5Hz (orange area) in the steady state domain. In this figure, f0 is defined as the value of the system frequency at time t2.

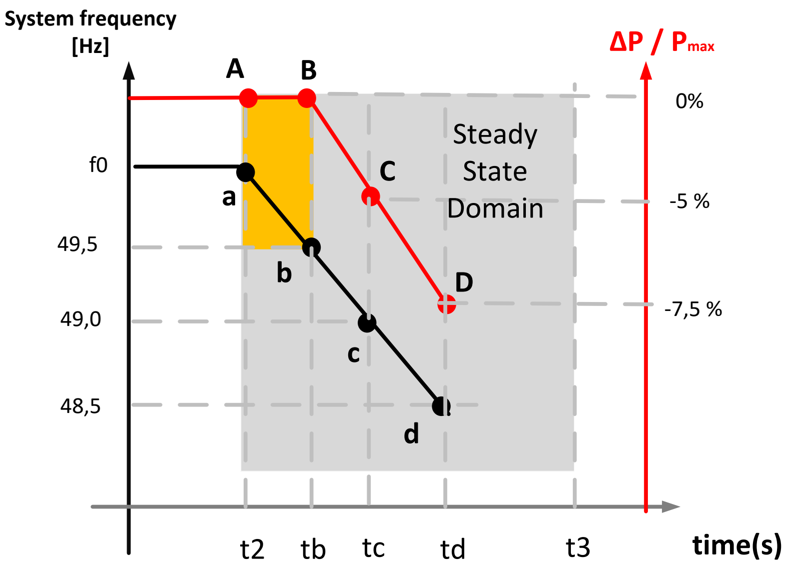

Figure 3. The maximum admissible active power reduction reflecting the steady state characteristic for the case of falling system frequency. The slope is taken as 10%/Hz.

Table summarises the recommended values of the requested capability for the transient as well as the steady state domain.

Figure 4 summarizes the proposed characteristics for the maximum admissible active power reduction at low frequencies for SPGMs and PPMs. For PPMs it is recommended to apply the transient characteristic for the whole time range, from **t1** up to **t3** with 2%/Hz slope.

Table 1 Recommended maximum admissible active power reduction (slope and frequency thresholds) at low frequencies for the national implementation for the transient and for steady-state domain given per synchronous area.

	Parameters	CE	Nordic	UK	IE	Baltic
transient domain	**frequency threshold**	49Hz	49Hz	49Hz	49Hz	49Hz
	slope	2%/Hz	2%/Hz	2%/Hz	2%/Hz	2%/Hz
	t1	≤ 2s	≤ 2s	≤ 2s	≤ 2s	≤ 2s
	t2	30s	30s	30s	30s	30s
steady-state domain (for SPGMs)*	**frequency threshold**	49,5Hz	49,5Hz	49,5Hz	49,5Hz	49,5Hz
	slope	10%/Hz	10%/Hz	2%/Hz	2%/Hz	10%/Hz
	t3	30min	30min	90min*	90min*	30min

* Except for CCGT where a minimum of 5min is requested.

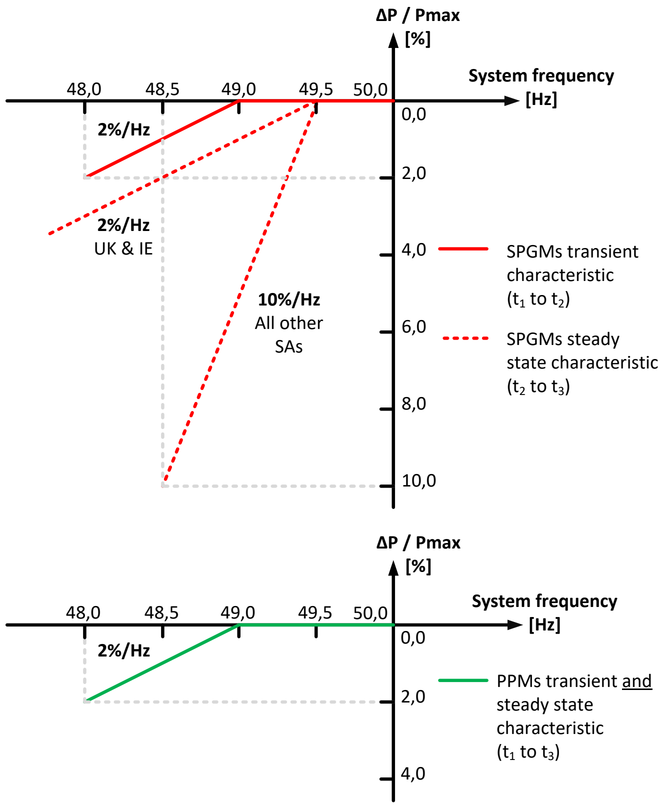

Figure 4. Maximum admissible active power reduction with falling frequency. The upper part of the figure presents the expected response of SPGMs in the transient domain (t1 to t2) and in the steady state domain (t2 to t3). The lower part presents the expected characteristic of the PPMs both for the transient as well as the steady state domain.

Furthermore, it is recommended for the national implementation of the NC RfG and for the compliance verification process the following to be defined:

- Initial voltage should be defined within the normal operation range. It must be acknowledged that deviation of the voltage outside the FRT profile or the steady-state voltage range allows PGM disconnection.

- Initial reactive power output at which the capability needs to be proven

- For PPM, the acceptability by the Relevant System Operator of a P over Q priority control scheme at low frequencies.

The ambient temperature should be specified at national level, based on geographic location specific conditions and system needs.

Concerning the national implementation of Article 13(5), it is recommended to require from SPGMs, **on a project-specific basis**, the inherent power vs. frequency characteristics (i.e. without any power compensation control measures) with the ambient temperature as a variable to be shown in the range between -10 to 40°C (see figure 5 an example for gas turbines). This shall not say that the above requirement is to be met for the whole set of temperatures but rather that this information is important for TSOs to be able to size FCR, FRR, and RR as well as the LFDD scheme and eventually minimum system inertia. Furthermore, the provision of this information will support the verification of compliance of the PGM with the defined requirement.

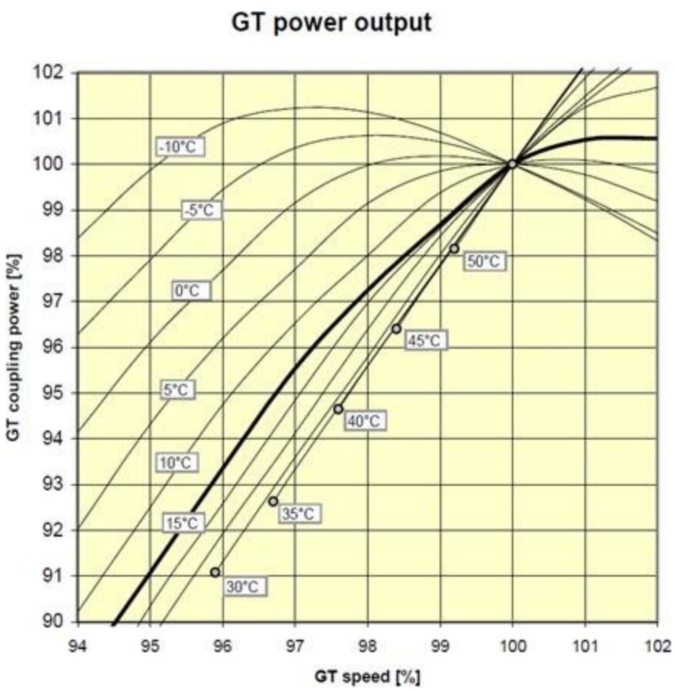

Figure 5. Minimum capability for basic design of existing gas turbines. It is important to note that this picture, does not present the minimum capability achievable at state-of-the-art basic design for all manufacturers. The figure presents typical behaviours of gas turbines.

As an example, the UK Grid Code defined the 25°C as the maximum temperature for which the requirements is applicable. Requirements with regard to maximum active power reduction at low frequency are expected to be applicable for CCGT for a limited frequency range, down to 48,8 Hz, where the under-frequency protection is set to trip (LFDD). It must be highlighted that CCGTs have been complying with the UK requirement for many years and have developed therefore efficient and cost-effective solutions. The capabilities of these CCGT designs should not be confused with the capability of existing CCGT based on a basic design as illustrated in the Technology Characteristics section below. Altitude between 400 m to 500 m and humidity between 15 to 20 g H2O/1 kg of air should also be defined.

During the implementation process of the NC RfG in Germany, manufacturers are further required to state the range of ambient conditions, where the steady state characteristic is met. Similar discussions have taken place in France, in NC RfG transposition forum, and have now provided proposals to the energy regulator and government. For generating units, whose behavior is dependent upon ambient condition (such as in the case of gas turbines turbines), the compliance is not expected for all ambient temperatures. It is expected that the inherent site-specific power vs. frequency characteristic be provided with the plant owner/manufacturer to the TSO, so that the TSO can analyse impacts. Instead of fixing a reference temperature, which will always be arbitrary and without real justification, it is recommended requiring from SPGMs, on a project-specific basis, the inherent power vs. frequency characteristics (i.e. without any power compensation control measures) with the ambient temperature as a variable parameter, to be used for system stability studies and design.

In addition to the above description of the recommended national implementation of the requirement of maximum admissible active power reduction at low frequencies, a clarification is deemed valuable to understand the interaction between this requirement and the requirements on LFSM-U and FSM. The IGDs on LFSM-U and FSM are defining additional net active power output[4] at low frequencies compared to the active power output delivered by the PGM at 50Hz. This additional net active power output should be demonstrated at the connection point and therefore it is expected that the control system acting on the power of the primary energy source should, in addition to the increase of this power compared to the 50Hz value, further increase this power to compensate for any active power reduction at low frequencies discussed within this IGD.

Technology characteristics

It is important to recall that this requirement defines the capability to maintain the rated active power output of a PGM in case of low frequency with relevance for plant design. **It is not an operational requirement and therefore the impact of the availability/unavailability of the primary energy source (e.g. water for hydro power plants) shall not be considered while assessing the compliance of a PGM with this requirement**.

[4] "where the "net active power output" is the active power exchange between the PGM and the network at the connetion point"

Furthermore, as mentioned in the system characteristics sections, the frequency of occurrence of large disturbance (i.e. outage of generation where the frequency drops 49,8Hz from nominal value) is expected to be rare. Therefore, it is not recommended to take into account a significant impact on the lifetime and maintenance intervals of the PGM in order to define the technical capability of the PGM when implementing the network code or assessing potential derogation requests.

Concerning the requirement itself, the relationship between frequency and active power output capability depends on the generation technology. There are synchronous generation technologies, in particular gas turbines, which have the inherent characteristic of losing some output at a lower frequency, i.e. at a lower rotational speed of the synchronous machine. This is not caused by a controller action but purely due to the physical fact that a lower rotational speed comes along with a reduced mass flow, which translates immediately into a reduced power output. This behaviour is strongly dependant on the ambient conditions. The ambient temperature has especially an impact: the higher the temperature, the higher the inherent and immediate output loss.

Gas turbines commonly operated in the power system include a shaft driven air compressor at the turbine inlet. When the CCGT is synchronously connected to the grid any disturbance in the system resulting in decrease of frequency will cause the compressor to slow down. This results in a reduction of the mass flow of air through the turbine and reduction of the active power output of the CCGT. This effect is much stronger at high ambient temperatures. Thus due to this physical phenomenon, gas turbine output drops significantly with falling frequency. To mitigate active power reduction, depending on the machine type and plant configuration different mitigation/compensation measures can be used (e.g. increasing the gas turbine flame temperature, increasing the air mass flow (by opening fully the compressor valves or by injection of water mist into the air intake of compressor)). This mitigation/compensation measures are limited in time and the support is expected to last as much the described in Table 1 (for the transit and steady state domain).

This phenomenon of decreased maximum power capability at low frequencies can be observed as well for other technologies used in the power sector especially if the low frequency is combined with low voltage. Due to reduction in efficiency of auxiliaries, the power generating units are not able to produce maximum power under these conditions. To mitigate this problem an appropriate choice of the auxiliary devices shall be considered at plant design.

ENTSO-E has conducted a consultation[5] directed to European stakeholders in order to collect the most up-to-date information concerning the capabilities (present and future) of generating units. According to the wind industry, wind farms based on full converter technology have very limited reduction of active power at low frequencies. Impact on active power is mainly due to auxiliary

[5] ENTSO-e, "Consultation of Stakeholders on Guidance for Connection Code Implementation of frequency related parameters", May 23rd – June 25th 2017.

equipment and change of losses in step-up transformers. Additionally, wind farms based on double feed asynchronous generator (DFIG) technology do need to reduce slightly more the active power at low frequencies to compensate the increase of current related to the decrease frequency.

These limitations for wind turbines technology do not prevent wind generation to comply with the most onerous specifications allowed by the RfG. Furthermore, the initial reactive power output and the acceptability of a P over Q priority control scheme at low frequencies could further increase the wind farm capabilities keep constant active power with falling frequencies. Some challenges have also been reported for other technologies, namely internal combustion gas engines or hydro units without that, taking into account the guidance provided in this document, the capability to fulfil the proposed implementation of this CNC requirement.

The most onerous specifications allowed by the NC RfG could however be a concern for gas turbines, especially at high temperature. Thermal overloading of the engine at lower frequencies is the main constraint for gas turbine and if the frequency set-point is kept for a longer time, power reduction must be performed below 49 Hz in order to avoid overloading of the engine. The hotter the ambient temperature, the lower the capability to maintain power output at falling frequency. For gas turbines, the decrease of active power is much less at low temperature. Typically, the engines start derating with a rate of 10 %/Hz and operate for unlimited time.

The gas turbine rating is typically specified at ISO condition (15°C).

Collaboration

TSO-DSO

As mentioned above, the transient characteristics should be coordinated at synchronous area level as this impacts the sizing of the FCR, UFLS scheme and eventually minimum system inertia. Strong benefits have been highlighted if structure of the requirement, ambient condition and steady state characteristics are also coordinated.

As per the NC RfG, this requirement is defined by the relevant TSO. It must be recalled that it is not an operational requirement.

RSO-Grid User

Specific attention should be given to the fact that some technologies are very sensitive to the specifications, in particular gas turbines. Discussion between RSO and power generating facility owner is strongly encouraged to ensure better understanding of technical limits of the generating module with taking into account the system needs.

Furthermore, the verification of compliance might be complex and shall be agreed with the power generating facility owner case by case.

Abbreviations

FCR	Frequency Containment Reserve	**PGM**	Power Generating Module
FRR	Frequency Restoration Reserve	**PPM**	Power Park Module
RR	Replacement Reserve	**RfG**	Requirements for Generators
DSO	Distribution System Operator	**RoCoF**	Rate Of Change Of Frequency
FSM	Frequency Sensitivity Mode	**RSO**	Relevant System Operator
LFSM-U	Limited Frequency Sensitive mode — Underfrequency	DFAG	double feed asynchronous generator
IGD	Implementation Guidance Document	**SPGM**	Synchronous Power Generating Module
CNC	Connection Network Code	**TSO**	Transmission System Operator
CNC RfG	Network Code on Requirements for Grid Connection of Generators, COMMISSION REGULATION (EU) 2016/631		
LFDD	Low Frequency Demand Disconnection	**CCGT**	Combined Cycle Gas Turbine

Annex1: National implementations in current grid connection codes

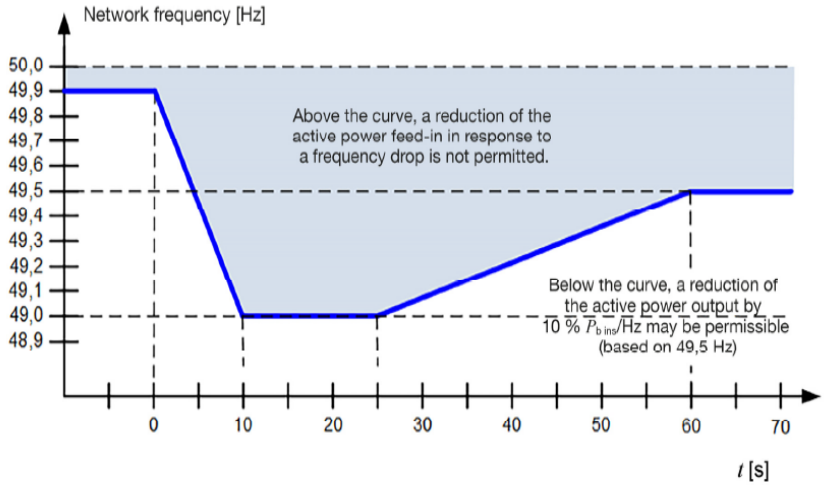

Figure 6 German Connection Network Code.

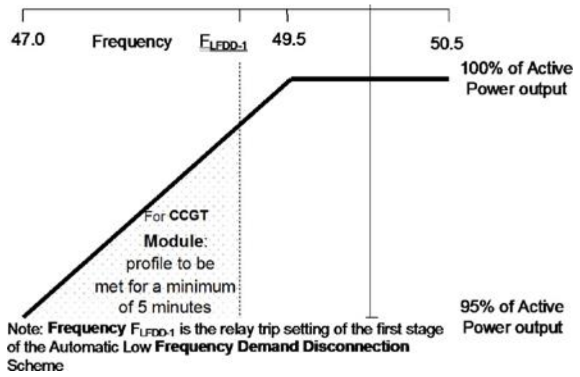

Figure 7 UK Connection Network Code

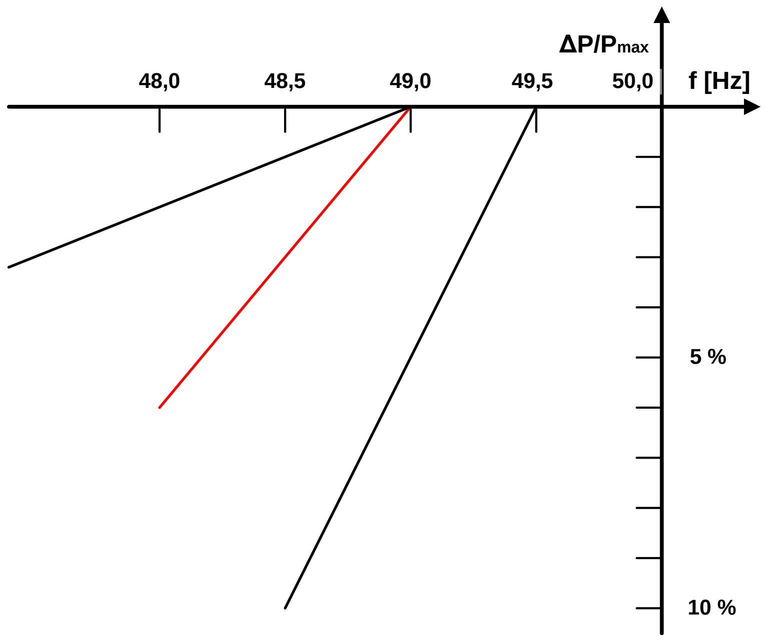

Figure 8 Danish Connection Code

Annex2: Link between GT characteristic and NC RfG non-exhaustive requirement.

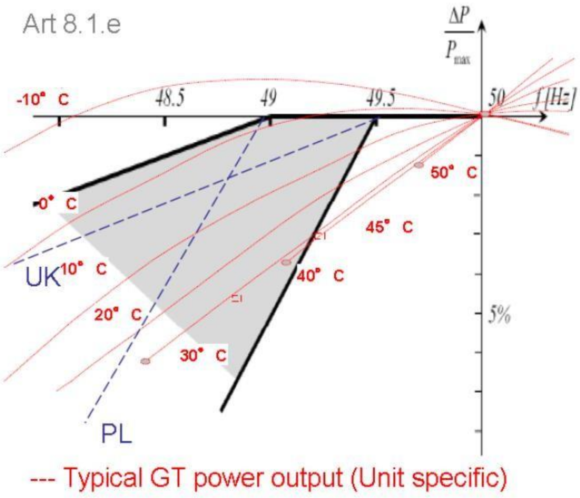

Figure 9 Example of active power output of a typical gas turbine with falling frequency (EU turbines year 2011)