European Network of
Transmission System Operators
for Electricity

Rate of Change of Frequency (RoCoF) withstand capability

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

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DESCRIPTION

Code(s) & Article(s)	NC RfG: Articles 13 (1) (b) and 15 (5) (b) (iii) NC DCC: Articles 28 (2) (k) and 29 (2) (g) NC HVDC: Articles 12 and 39 (3)
Introduction	The requirement aims at ensuring that power generating modules (NC RfG), demand units offering Demand Response (DR) services (DCC), HVDC systems and DC-connected power park modules shall not disconnect from the network up to a maximum rate of change of frequency (df/dt). A large rate of change of frequency (RoCoF) may occur after a severe system incident (e.g. system split or loss of large generator in a smaller system). The facilities shall remain connected to contribute to stabilize and restore the network to normal operating states. The resulting RoCoF withstand capability will be an important input to calculate the essential minimum inertia (provided by the synchronous PGM with inherent inertia and by PPMs with synthetic inertia) for system stability in case of outage or system split, incl. asynchronous operation of control block. Therefore there is a direct link between RoCoF and inertia related requirements. Please note that this IGD would be updated in respect to frequency measurement criteria once the outcome of task force on this topic is finalized and published.
NC frame	NC RfG and DCC require that the Relevant TSO shall specify the df/dt (RoCoF), which a power generating module (RfG) or a Demand Unit (DCC) shall at least be capable of withstanding. <u>NC HVDC</u> • Article 12: An HVDC system shall be capable of staying connected to the network and operable if the network frequency changes at a rate between – 2,5 and + 2,5 Hz/s (measured at any point in time as an average of the rate of change of frequency for the previous 1 sec). • Article 39 (3): DC-connected power park module shall be capable of staying connected to the remote-end HVDC converter station network and operable if the system frequency changes at a rate up to +/– 2 Hz/s (measured at any point in time as an average of the rate of change of frequency for the previous 1 second) at the HVDC interface point of the DC-connected power park module at the remote end HVDC converter station for the 50 Hz nominal system. NC DCC, Article 28 (2) (k): • Demand units with demand response active power control (...) shall have the withstand capability to not disconnect from the system due to the rate-of-change-of-frequency up to a value specified by the relevant TSO. With regard to this withstand capability, the value of rate-of-change-of- frequency shall be calculated over a 500 ms time frame.

Further info	Further implementation guidance on NC RfG, DCC and NC HVDC: Supporting documentation of HVDC network code: • Network Code for HVDC Connections and DC-connected Power Park Modules - Requirement Outlines (30. April 2014) External supporting documents: 1. EirGrid, Soni, *All Island TSO Facilitation of Renewables Studies* 2. EirGrid, Soni, *Summary of Studies on Rate of Change of Frequency events on the All-Island System* (Aug 2012) 3. NationalGrid, *Electricity Ten Year Statement 2012*, *Chapter 4* 4. NationalGrid, University of Strathclyde, *Loss of Mains Protection* 5. DNV-GL, EirGrid, *RoCoF Alternative Solutions Technology Assessment (Phase 1 and Phase 2)* 6. EirGrid, *Increased Wind Generation in Ireland and Northern Ireland and the Impact on Rate of Change of Frequency* 7. ENTSO-E WG SPD, *Frequency Stability Evaluation Criteria for the Synchronous Zone of Continental Europe* 8. *IGD on High Penetration of Power Electronic Interfaced Power Sources* 9. M. Chan, R. Dunlop, F. Schweppe: "*Dynamic Equivalents for Average System Frequency Behaviour Following Major Disturbances*," IEEE Transactions on Power Apparatus and Systems 10. S. Engelken, C. Strafiel, E. Quitmann: "*Frequency Measurement for Inverter-based Frequency Control*," in Wind Integration Workshop, Vienna, 2016 11. NationalGrid. Energy Networks, *Frequency Changes during Large Disturbances and their Impact on the Total System* 12. Fraunhofer ISE, Energy Charts (https://energy-charts.de/power_de.htm) 13. KEMA-DNV, EirGrid, *RoCoF An independent analysis on the ability of Generators to ride through Rate of Change of Frequency values up to 2Hz/s*

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INTERDEPENDENCIES

Between CNCs	The selection of the maximum (df/dt) values to be withstood needs to be chosen by collaboration between the connection codes in order to ensure equitable behaviour of the relevant system users in case of rapid frequency changes bearing in mind the different scope of application of the CNCs. NC HVDC introduces an explicit limit for HVDC systems (2.5 Hz/s), which is above the limit for DC-connected power park modules (2.0 Hz/s). The rationale behind these choices is to have a margin between the capability of HVDC systems and power generating modules to ensure that HVDC systems will disconnect last in order to enable power generating modules and demand units to contribute to stabilize and restore the network to normal operating states as long as possible.
With other NCs	**COMMISSION REGULATION (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation**, adopted by the EC on 04.05.2016, Article 39 (“Dynamic stability management “)

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System characteristics	Rate of change of frequency RoCoF is the time derivative of the power system frequency (df/dt). This quantity was traditionally of minor relevance for systems with generation mainly based on synchronous generators, because of the inertia of these generators, which inherently counteract to load imbalances and thus limit RoCoF in these cases. It however becomes relevant now during significant load-generation imbalances (caused by disconnection of either large loads or generators, or by system splits), when larger RoCoF values may be observed because of low system inertia caused by (amongst others) disposal of synchronous generation in case of high instantaneous penetration of non-synchronously connected generation facilities. In the absence of any control, inverter-based generation does not possess such inherent characteristics and high inverter penetration could therefore lead to higher df/dt in a power system. The relationship between inverter penetration and RoCoF is, however, not straightforward, and countermeasures – mostly in the form of control algorithms – need to be implemented carefully. Large df/dt values may endanger secure system operation because of mechanical limitations of individual synchronous machines (inherent capability), protection devices triggered by a particular RoCoF threshold value or timing issues related to load shedding schemes. Initial df/dt is the instantaneous RoCoF just after the disconnection of either a generator or load from a power system, before any controls become active. This is theoretically the highest system RoCoF. Its average for an interconnection of *N* synchronous loads and generators can be computed as follows: $$\left.\frac{d\Delta f}{dt}\right\|_{t=0^+} = \frac{f^0 P_k}{2\sum_{i=1,i\neq k}^{N} H_i S_i}$$ wherein Δf is the deviation of the frequency *f* from its nominal value f^0, 0^+ is the moment just after disconnection of the load/generation P_k is the lost generation/load (the machine carrying the index k), and H_i and S_i are the inertial constant and apparent power rating of synchronous machine *i*, with i ranging from 1 to *N* [9]. Additional frequency oscillations may occur locally on top of the average behavior. It should be noted that any system that relies on measuring frequency and df/dt will most likely not detect a RoCoF as high as the theoretical maximum. This is due to the inevitable filtering involved in frequency measurement [10]. As a result, RoCoF relays with measurement windows of several hundred ms may not be triggered if the initial df/dt exceeds their threshold, but RoCoF is lower subsequently. To define the RoCoF withstand capability correctly, the characteristics of an entire synchronous area must be considered. The capability shall be determined based on analysis of a normative incident for the network concerned. Such a normative incident could be a system split in a large synchronous area with a significant change of inertia and power imbalance in the resulting subsystems (e.g. historic events like the Italy blackout in 2003 and the Continental Europe 3-way split in November 2006). With regard to smaller synchronous areas with low inertia the loss of the largest power generating module or HVDC link may define the normative incident instead (e.g. increase of loss of a single unit up to 1800 MW in GB which would commonly exceed the until recent existing GB threshold level of RoCoF-based Loss of Mains (LOM) protection [0.125 Hz/s]) [11].

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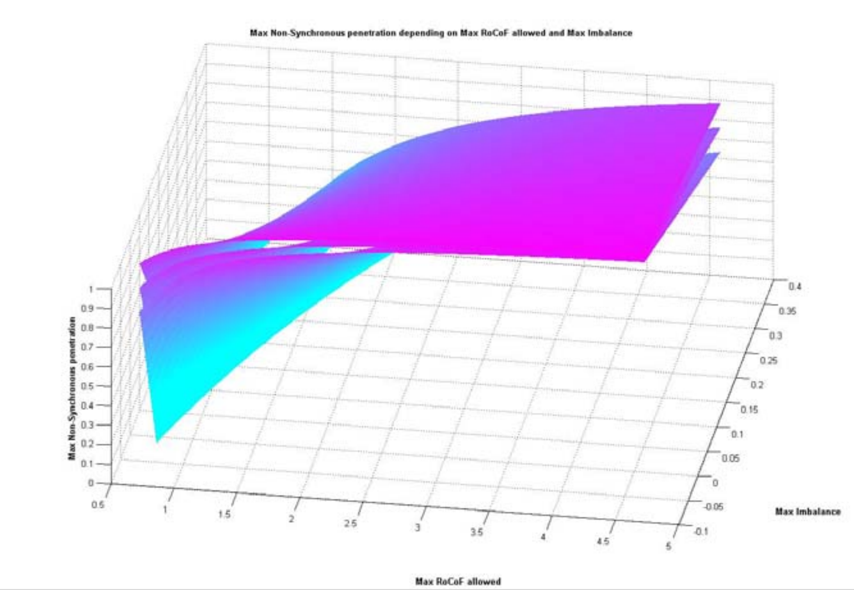
Since one main concern is the decrease of system inertia, chosen scenarios should reflect situations with low inertia, e.g. high share of non-synchronous renewable generation or high import/export scenarios in case of system splits. For example, on 23rd of August 2015, renewable energy generation in Germany covered 84% of domestic demand [12].

Given the uncertainty on system characteristics and their future evolution, power generating modules need to be robust against changes to the system and shall provide RoCoF withstand capability which accounts for these varying system conditions (e.g. in Ireland, simultaneous penetration by non-synchronously connected generation shall be increased to 75% by 2020, which has significant implications for the RoCoF)



Maximum system penetration with reference to RoCoF and system imbalance for the synchronous generation operating at 50%, 75% and 100% of rated output (extracted from "Frequency Stability Evaluation Criteria for the Synchronous Zone of Continental Europe", SPD WG, ENTSO-E).

The RoCoF withstand capability should be assessed on not only the present network but also account for the expected capability that will be required over the asset life of concerned installations accounting for future changes in the network and its demand and generation portfolio. Also the capability of existing connected generators will be taken into account.

The RoCoF withstand capability should ideally be provided as a change in frequency over a defined time period which negates short term transients and therefore reflects the actual change in synchronous network frequency). However, in practice this may interfere with protective controls of generators or LOM schemes. Hence, changes relevant to protections, e.g. LOM, using RoCoF but driven by other needs can be considered. Other LOM protection systems (e.g. inter-tripping, satellite protection and load shedding [4]) might also be considered as alternative measures.

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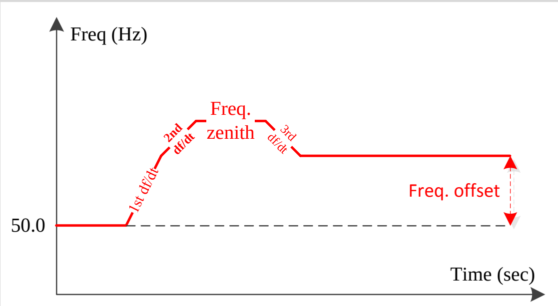
	Finally, All-Island studies show large df/dt deviation after an event between different bus-bars for the first few cycles, eventually converging to one value, pointing to the importance of the length of the measurement time window for calculation of df/dt [2].
Technology characteristics	Although the inherent capability may vary for different generation technologies, a single minimum RoCoF withstand capability may be required to ensure stability of the network. A common value of RoCoF withstand capability of a synchronous area shall not inhibit a TSO requiring further inherent withstand capabilities not to be unreasonably withheld e.g. to manage system operation of parts of its network which may be exposed to a higher risk of islanding. Dissimilar capability thresholds may apply for different technologies (e.g. thermal power generating modules and wind turbines) if applicable and technically and economically appropriate (based on stakeholder survey results, wind turbines can stay connected with no problem while df/dt goes as high as 4 Hz/s while synchronous power generating modules can at least withstand 2.5 Hz/s with 100 ms time-window). Factors such as rigidity of connection point, repetition of high df/dt events and stability of plant's auxiliary machines may be taken into account. The main concerns of thermal power generating modules about high RoCoF are instability and reduced life time of their assets (both electrical and mechanical) due to wear and tear. Since df/dt capability was not a design requirement historically, no specific design criteria or controller system features to counter high df/dt events as well as no protection scheme to disconnect purely due to df/dt measurements have been reported to ENTSO-E. DNV KEMA studies for Irish TSOs [13] also show the dependency of individual unit stability on time window size and feasible df/dt values. This again indicates the importance of time window size. In addition, operation of power generating modules in leading power factor mode will increase their vulnerability to high RoCoF values. Loss of Mains RoCoF type protection & settings, although not explicitly part of Article 13 (1) (b) of NC RfG, are covered in Article 14 (5) (b) on Protection Coordination. These requirements should be carefully set by collaboration.
Proposal	Since the withstand capability strongly depends on rigidity (short circuit power) of the connection point, technology, design specification and operation point of the power plant, one TSO may define different withstand capabilities in reference to such parameters. On the other hand, available inertia in the synchronous area (based on generation mix and HVDC connections in both current and future scenarios) is an important factor in defining max/min possible df/dt events which affect the decision of TSOs inside SA whether there is a need for stringent or more flexible requirements. Relevant TSO shall specify the pre-fault and post-fault conditions for the RoCoF withstand capability in terms of: • pre-fault minimum short circuit capacity at the connection point, • pre-fault active and reactive power operating point of the power-generating module at the connection point and voltage at the connection point, and • post-fault minimum short circuit capacity at the connection point;

Alternatively, the relevant system operator may provide generic values derived from typical cases.

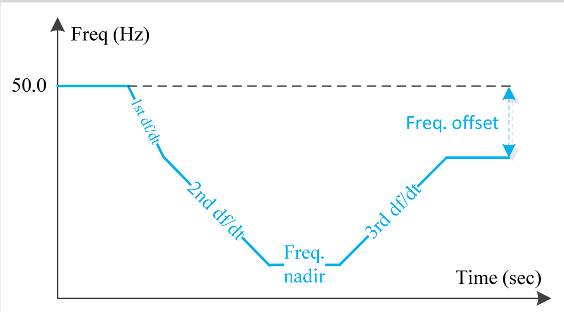
The TSO may define the withstand capability requirements as a set of frequency-against-time profiles. The frequency-against-time-profiles shall express lower limits for under-frequency and upper limits for over-frequency of the actual course of the frequency deviation in the network as a function of time before, during and after the frequency event. Such profile should include:

- frequency nadir/zenith
- steady state frequency offset
- the duration that the user has to stay connected
- and consecutive df/dt ramps

The following profiles are given as an example for both over-frequency and under-frequency profiles:



Proposed Over-frequency profile



Proposed Under-frequency profile

Based on results from studies and better harmonization between the connection codes, RoCoF measured at any point in time as an average of the previous 500 ms, is the most reasonable proposal for the minimum RoCoF withstand capability. This capability is to be verified with a specific /predefined frequency profile and explicit measuring technique. Following profiles are hence the WG CNC recommended profiles taking 2.0 Hz/s for duration of 500 ms as the minimum RoCoF to be withstood. TSOs in smaller SAs may define a second swing as well to represent the more realistic behaviour of their system.

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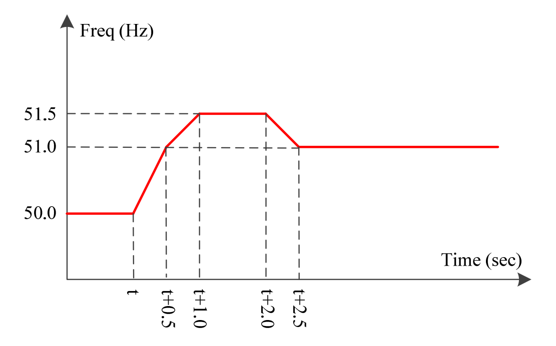
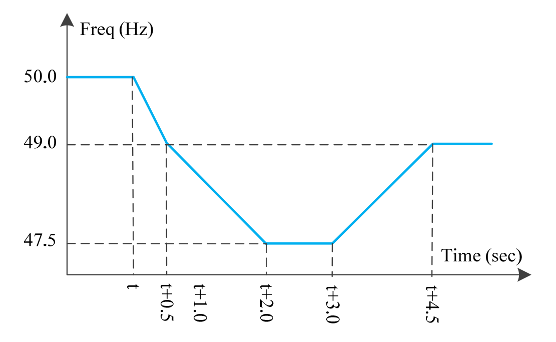


Proposed Over-frequency profile



Proposed Under-frequency profile

COLLABORATION

TSO – TSO	Although not explicitly requested in the connection network codes, it would be reasonable to consider collaboration for the RoCoF withstand capability criteria (including) within each synchronous area. This includes the maximum RoCoF value to be withstood, the duration of the measurement rolling window but also frequency and RoCoF measurement criteria. Therefore, TSO – TSO collaboration within a synchronous control area would ensure that a minimum RoCoF withstand requirement is applied to all relevant system users.
TSO – DSO	Based on article 13 (b), a power-generating module shall be capable of staying connected to the network and operate at rates of change of frequency up to a value specified by the relevant TSO, unless disconnection was triggered by rate-of-change-of-frequency-type loss of mains protection. The relevant system operator, in coordination with the relevant TSO, shall specify this rate-of-change-of-frequency-type loss of mains protection.
RSO – Grid User	The relevant system operator needs to take care, that the parameters of RoCoF withstand capability defined by the relevant TSO are applied to system users.