European Network of
Transmission System Operators
for Electricity

Need for synthetic inertia (SI) for frequency regulation

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

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Table of Contents

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DESCRIPTION

Code(s) & Article(s)	**NC RfG** - Article 21.2(a): The relevant TSO shall have the right to specify that power park modules [of type C and D] be capable of providing synthetic inertia during very fast frequency deviations. **NC HVDC** - Article 14.1: If specified by a relevant TSO, an HVDC system shall be capable of providing synthetic inertia in response to frequency changes, activated in low and/or high frequency regimes by rapidly adjusting the active power injected to or withdrawn from the AC network in order to limit the rate of change of frequency. **NC DCC** – Article 30.1: The relevant TSO in coordination with the relevant system operator may agree with a demand facility owner or a closed distribution system operator (CDSO) (including, but not restricted to, through a third party) on a contract for the delivery of demand response very fast active power control.
Introduction	It is the objective of this IGD to provide guidance on synthetic inertia (SI) aspects to be considered when choosing relevant national parameters and opting in or out of non-mandatory requirements. It should be noted that this document provides guidance when the relevant TSO is experiencing or foreseeing modest penetration of RES. The challenge of maintaining frequency stability increases dramatically when total system inertia decreases and to safeguard such situations, the IGD on High Penetration of Power Electronic Interfaced Power Sources introduces more holistic and effective approaches. System inertia is an essential parameter for frequency stability of the energy supply system as it is a determining factor for frequency changes in case of load imbalances in the system (frequency sensitivity). As a result of displacement of conventional synchronous power generating modules, whose rotating masses inherently contribute to system inertia by power park modules connected through power electronics and growth in application of power electronic drives at the demand side, the total system inertia tends to decrease. This decrease will accelerate with the continuous changes of the generation portfolio resulting in increased frequency sensitivity if no countermeasures are taken. In this regard SI may become an essential aspect in context of frequency stability. The need for SI applies for smaller synchronous areas with high penetration of non-synchronous generation which tend to have lower total system inertia and greater frequency sensitivity (such as Ireland and Great Britain), but also to large synchronous areas to prevent total system collapse in case of a system split and subsequent island operation. From a system operation perspective it can therefore be of crucial importance that all generators (type C and above), HVDC systems and suitable demand units are able to provide SI. SI could then facilitate further expansion of RES, which do not naturally contribute to inertia. However, it will have to be considered that depending on the way how in future synthetic inertia will be provided the dynamic system response will differ and the current control principles will have to be adapted correspondingly!

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NC frame

RfG defines synthetic inertia as the facility provided by a power park module or HVDC system to replace the effect of inertia of a synchronous power generating module to a prescribed level of performance. Based on Article 21 (2) (b) of RfG, the operating principle of control systems installed to provide synthetic inertia and the associated performance parameters shall be specified by the relevant TSO. Hence, RfG focuses on the performance requirement of the SI from a functional perspective rather than details on technical implementation to achieve the objectives.

There are two distinct challenges.

1. Limit the system initial rate of change of frequency (RoCoF) – df/dt

The initial RoCoF after a worst case disturbance needs to be kept below the maximum capability of users (demand and power generation units) to remain connected. User limitations include both control system robustness for high df/dt (including existing conventional plant) as well as use of df/dt for island detection and Loss of Mains (LOM) protection for embedded generators. For these aspects a form of SI contribution may be required within a few 100 ms.

2. Limit the lower/higher nadir of the frequency to avoid demand/generation disconnection.

Limit how deep/high the frequency falls/rise after a major disturbance (using largest infeed loss as the criterion). A fast activated contribution contribute to raise the nadir above the first stage of demand disconnection. In this context, SI (possibly initiated by df/dt criterion and power increase proportional to df/dt) is not likely to be essential. Fast frequency response (delivered in the very first seconds) may be an alternative or supplement as reaching the nadir is likely to take several seconds.

These two aspects are illustrated in the following figure (extracted from the National Grid Electricity Ten Year Statement 2014)[1].

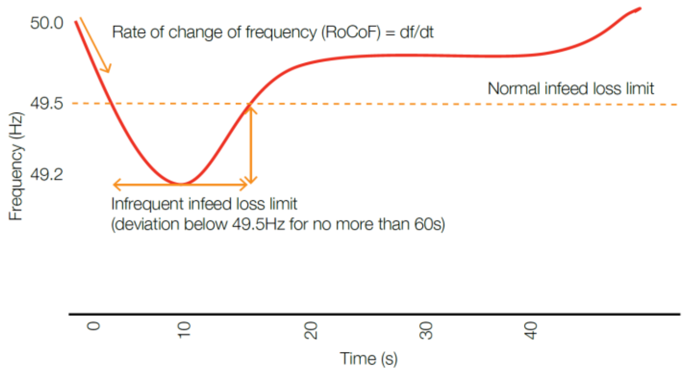

FIGURE 1. SYSTEM FREQUENCY LIMITS AND CONCEPT OF ROCOF REF.[1]

Further info	IGD on High Penetration of Power Electronic Interfaced Power Sources KEMA: "Technical report on ENTSOE Network Code: Requirements for generators" (see attachment) RoCoF Alternative Solutions Technology Assessment (see attachment) Frequency Response Study - California ISO(see attachment) Dynamic Frequency Response of Wind Power Plants (see attachment)

[1] http://www2.nationalgrid.com/WorkArea/DownloadAsset.aspx?id=37790

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	Understanding Inertial and Frequency Response of Wind Power Plants (see attachment) Grid Code Frequency Response Working Group, National Grid (see attachment) Tutorial of Wind Turbine Control for Supporting Grid Frequency through Active Power Control (see attachment) Frequency Response Initiative, NERC (see attachment) IGD - Rate of Change of Frequency (ROCOF) withstand capability Frequency Stability Evaluation Criteria for the Synchronous Zone of Continental Europe[2]

INTERDEPENDENCIES

Between the CNCs	All CNCs allow introducing synthetic inertia (RfG and HVDC) or very fast active power response (DCC).
With other NCs	COMMISSION REGULATION (EU) …/… of XXX establishing a Guideline on Electricity Transmission System Operation, adopted by the EC on 04.05.2016, Article 39 ("Dynamic stability management ")
System characteristics	<u>Consideration for problem 1 Initial df/dt</u> Use of RoCoF as a Loss-of-Mains (LOM) protection is the largest concern in respect of high initial df/dt, because of potential tripping of embedded generators through mal operation of the protection when the embedded generation is not islanded, but simply subject to a system wide fast frequency movement. A significant further challenge for some control units is stability aspects of control systems of power generating modules during high RoCoF. See second example concerning R&D early evidence of possible adverse effects related to the converter control type of control associated with implementation of SI. Traditional per unit system inertia H for a synchronous generator dominated system is of the order of 5-6 sec (or $T = 2{\cdot}H = 10$-12 sec). This varies from country to country with types and specification of generators. Future system design considerations may need to establish the lowest allowable per unit system inertia at synchronous area level under the most challenging conditions, which may be defined by a normative incident. Each TSO is responsible for establishing its minimum necessary inertia for secure operation in case of relevant incidents with regard to its area of responsibility (loss of generation or system split). It is also necessary that each TSO establishes its maximum load imbalance to be withstood after a system split or loss of generation. Selection of the maximum load imbalance robustness target value and its consequences is extensively covered in the ENTSO-E report "Frequency stability evaluation criteria for the synchronous zone of Continental Europe – Requirements and impacting factors" with a suggested conclusion of a desired capability of robustness up to 40% load imbalance. In this regard, each TSO/control block should consider its capability to provide the necessary inertia in case of system split for its individual stability in addition to contribution to overall synchronous area inertia. The expected initial df/dt should be calculated and it may be managed actively in operational timescales in context of existing df/dt robustness (such as legacy low RoCoF in Great Britain (GB) at 0.125Hz/s). To remove such costly operational

[2] https://www.entsoe.eu/Documents/SOC%20documents/RGCE_SPD_frequency_stability_criteria_v10.pdf

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limitations (e.g. redispatch and renewable energy curtailment) considerations should be given to actions to secure total system inertia under normative conditions. This may require an action to avoid H going below the target value (future system design should calculate and define what is the lowest allowable p.u. H which should cover the most challenging conditions) by combination of:

- SI contribution from future Power Park Modules (PPMs), e.g. to require minimum contribution such as H=3s.
- SI contribution from HVDC links.
  - If the energy is drawn from another system consideration of the impact on that system is needed.
  - Alternatively, a short burst of active power for the purpose of limiting the initial df/dt can be drawn from the capacitive energy on the DC link[3]. This applies also to the DC links of PPMs[4]. However, the stability/dynamic effects and consequences/performance of such method should be carefully studied/considered.
- Demand Response (DR) very fast system frequency control (autonomous).

Additionally, it is a requirement to consider market alternatives. The case of Ireland could be investigated to explore this possibility. Consideration should also be given to the effectiveness of mandatory capabilities while leaving the utilisation of these to the market, in this case an inertia market, which may be very challenging to establish. Since before activation of SI in the system (100-500 ms) the df/dt might be very high, relevant TSO should make sure that all units can survive the initial RoCoF. Studies show that SI can significantly reduce the average RoCoF after activation[5]. On the other hand, some research show that common control philosophies used may cause new stability challenges. This aspect may be solved by using more advance control methods (see second example with associated reference).

Aggressive SI might lead to second frequency swing which should not be immediately treated as a negative reaction. If reduction of df/dt is the main concern of a TSO, SI over-react might be useful if relevant TSO can manage the second swing via other measures (e.g. by delivery of frequency sensitive mode (FSM)). Also, parameters such as wind speed or solar radiation, demand size and available SI needs to be taken account of to determine the need and the scale of SI[6].

Considerations for problem 2. Limit the lower nadir of frequency for largest loss or system split.

After withstanding the initial RoCoF (limited by either inherent inertia alone or combined by SI) after an outage or system split, the next challenge is to minimize the deviation of frequency nadir from reference frequency. Different studies (e.g. TRANSNET Frequency response study (see attachment) show that in such cases, the primary frequency response can be too little and too slow to be able to reduce the frequency nadir. Meanwhile, SI can be very effective, benefiting from the speed and controllability of power electronic links.

Frequency response from wind farms has been common in several countries for

[3] http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6319376
[4] http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7005036
[5] see attachment Frequency Response Study - California ISO
[6] http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6265353

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	more than 10 years. See examples of existing grid codes and regulation drafts at the end of this document.
Technology characteristics	Many patents and studies have investigated the measures and technical aspects of providing SI via power park modules and HVDCs. This includes the ability to charge/discharge energy into/from wind turbine blades, magnetic fields of machines and also DC link capacitors using different control schemes. Hence, the technical feasibility of SI is not an issue by principle (although may it be not mature enough presently and need more time for further technical enhancement). A main challenge relates to frequency measurement. TSOs shall define the size of measurement rolling window, the acceptable delay time (which includes the measurement, processing and operation time), possible activation trigger and functionality rather than measuring technique and control method details. This may vary dependent upon the characteristics of the Synchronous Area (SA). The measurement challenge will increase if the control system is based on the df/dt. Based on the Dynamic Stability Assessment findings, each TSO choosing to apply SI shall define at least the following requirements for the relevant elements: • Measuring time window for calculation of frequency or df/dt and total delay time • Function characteristics (e.g. df/dt vs. Δf, deadband and droop) • TSO input signal for activation and access to alter settings such as droop The above considerations require a well-founded strategy to deal with: • potential measurement limitations such as fast transient movements of “frequency” (local angular movements), • technical and operational limit of SI exploitation, • the possibility to increase the size of DC-Link capacitors for storing more energy, and • DR capabilities and likelihood of participation (technical limits).

COLLABORATION

TSO – TSO	Based on the Guideline on Electricity Transmission System Operation, all TSOs of that Synchronous Area shall conduct studies to identify if a need exists for the definition of the minimum required inertia. Each TSO is entitled to define and deploy in operation the minimum inertia in its own Responsibility Area. This calls for cooperation among TSOs in a SA in sharing necessary technical data, expertise and results.
TSO – DSO	Interaction between Loss-of-Mains protection based on RoCoF where these are applied (i.e. GB and Ireland) and df/dt in system incidents needs to be considered. In particular, RfG requires the relevant system operator to collaborate with the relevant TSO the specification of RoCoF-type loss of mains protection, which also interacts with the necessary system inertia.

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RSO – Grid User

Example(s):

Conventional frequency response for wind farms in existing grid codes

The GB Grid Code has since 2005 required similar demanding frequency response from large PPMs (starting at 10MW in North of Scotland) as for synchronous generators (response proportional to frequency deviation from target (10% at 0,5Hz) delivered within 10 seconds, with an initial delay less than 2 seconds). Low frequency capability is in the main preparation for longer term future with very high non-synchronous generation (NSG) penetration (with diminished FSM from synchronous generators (SGs)). However, at an earlier stage high frequency response delivered without head room is of particular value for high frequency control under low demand. This is when many of the SGs providing frequency response are operating at minimum generation (unable to respond to a high frequency excursion). Additional features have more recently been added to FSM for PPMs to virtually avoid all loss of energy capture while selected to deliver just a high frequency FSM response service.
Commission of Energy Regulation of Ireland requires wind farms to control their active power output in response to frequency change outside a dead band. The document defines a droop response based on size and technical parameters of PPM and specifies no activation time delay except technical restrictions. The minimum response is 1% of rated power per second (see attachment - CER -Wind Farm Transmission Grid Code Provisions).

In Denmark, wind farms connected to voltage level above 100kV should be equipped with frequency-controlled power generation to respond to frequency deviation with a droop between 1-10% of its rated power (see attachment - DEA -Wind turbines connected to grids above 100 kV).

In Canada, wind farms of nominal size greater than 10MW, if frequency deviation is greater than 500 mHz, the PPM should be able to emulate an inertia of minimum H = 3.5 sec for 10 seconds (see Hydro Quebec - technical requirements for connecting generation).

Potential adverse effects from certain types of SI control strategies.

It has been demonstrated in research context that power systems with very high NSG may go unstable at frequencies up to 10 Hz. See [Use of an Inertia-less Virtual Synchronous Machine within Future Power Networks with High Penetrations report -attachment] which report current status of R&D work on this topic, supported by a TSO. This document in turn contains further references. Many factors influence the point at which steady state stability is at risk at a given level of Instantaneous Penetration Level (IPL) of converters. Most noticeable is the selection of control strategy for the converters.

In context of frequency stability, high IPL is also associated with challenges of high RoCoF when the power balance is suddenly subject to a large disturbance, due to diminished total system inertia. Possible solutions to this aspect include consideration of synthetic inertia (SI). Research has shown that some forms of SI may make the steady state stability worse. This appears to include dq-axis controllers with current injection (DQCI controllers) with Swing-Equation-Based-Inertial-Response (SEBIR). The negative impact of SEBIR on steady state stability is heavily dependent upon measurement of df/dt or RoCoF. Early results applying measurements of ROCOF using an M-class Phasor Measurement Unit (PMU) window (11 cycles) seems to provide higher system stability than using P-class PMU windows (3 cycles), although there are many variables and parameters which concurrently affect the results and this is not a firm conclusion at this stage. See the report Use of an Inertia-less Virtual Synchronous Machine within Future Power Networks with High Penetrations. See also IGD RoCoF withstand capability.

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The report *Use of an Inertia-less Virtual Synchronous Machine within Future Power Networks with High Penetrations* goes on to evaluate mitigating action through choice of a different control strategy, of which there are likely to be several. It considers moving from a "following" strategy to a "leading" strategy (one of which it calls VSM0H) showing steady state stability with higher penetration (IPL).

Risk management considerations

TSOs in a SA shall conduct a collaborative study/procedure to define the possibility and risks of different system split scenarios to conclude/determine:

- the range of circumstances that one TSO wishes to withstand
- how much each TSO/country shall to contribute to total min SA inertia
- how large % of time does each country have to contribute their share

to ensure that nominative split event (e.g. 40% power imbalance) can be coped with.

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