Expert group: Advanced capabilities for Grids with a High Share of Power Park Modules

Draft Final Report
Version 0.9

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Summary

This report is presented to GC-ESC by the Expert Group Advanced Capability of Power Park Modules (ACPPM).

Based on the TOR of the ACPPM and the work done in the expert group, the report provides the following information:

The first four chapters are introduction with in chapter 2, the state of knowledge.

- Chapter 5 gives an overview of the terms and definitions, used is in this report.
- A qualitative description of the system needs in chapter 6 and provides a general statement on how these needs could be provided by grid-forming power park modules (PPM).
- The potential issues for distribution networks, as a consequence of the connection of massive numbers of grid forming generation in MV and LV networks, are highlighted in chapter 7.
- An overview of the capabilities, limits and technology readiness of various power generating technologies and grid asset technologies to provide for these needs in chapter 8. In this chapter not only are PPM and converter based technologies reviewed, but also Synchronous Power Generating Modules (SPGM) and rotating condensers.
- Recommendations for developing the compliance verification and compliance monitoring for the new grid forming requirements in chapter 9.
- Information on possible paths to deliver these capabilities in chapter 10.

Based on the technical discussion in chapters 2 to 10 a legal text proposal has been developed that is proposed for the upcoming revision of the network code requirements for generation in chapter 11.

Chapter 12 concludes with a summary of recommendations as stated in the chapters of this report. In summary these are:

- Undertake more research into the effects of high penetration of grid forming converters in DSO networks, including in particular stability issues.
- Initiate a programme of creation of relevant standards, which should also include conformity tests and models for digital simulations.
- Implementation should be phased, recognizing the developing maturity of the understanding of the effects of an interactions of grid forming converters (GFC).

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1 History of the expert group Advanced capabilities for Grids with a high share of Power Park Modules

On 07 December 2021, the Grid Connection European Stakeholder Committee (GC ESC) formally initiated establishing an expert group (EG) to review the Advanced capabilities for Grids with a High Share of Power Park Modules.

The ESC proposal for the expert group was based on a stakeholder survey to identify priority topics for which future revisions to the CNCs could be considered.

Initially no-one volunteered for chair/vice-chair leading to a short delay in the starting process. In the end 3 persons volunteered for chair/vice-chair.

The EG started its work in April 2022. The outcome of the EG is documented in this report which will be addressed to the Grid Connection European Stakeholder Committee (GC ESC) for consideration and acknowledgement. The report can be the basis for official introduction of relevant amendments to the CNCs by ACER.

The Terms of Reference were approved by the GC ESC 02 March 2022.

2 State of knowledge

2.1 Objectives and motivation

Maintaining the stability of the European interconnected power system has been identified as one of the key challenges to enable energy transition by ENTSO-E [2-1]. Transitioning conventional synchronous generator-based generation to converter-interfaced renewables imposes great stability challenges due to reduced inertia and short-circuit power. Various working groups and research projects at both national and European level have investigated system needs, technical challenges and possible solutions for converter dominated power systems [2-2, 2-3, 2-4, 2-5, 2-6, 2-7, 2-8]. However, the network connection codes do not yet reflect many of the necessary capabilities for stable and robust operation during normal, alert and system restoration states when considering the future very high penetration of PPMs and low system strength (inertia and short circuit power). For meeting such future system needs new capabilities need to be defined and harmonized in the three connection network codes – as already stated in the ENTSO-E position paper [2-9] - and therefore these codes also have to include converter-based generators besides more traditional solutions (for instance, synchronous condensers with flywheel, etc.).

Building upon the knowledge in the current literature, this expert group has undertaken to:

1) give guidance at EU and national level how power system needs for advanced capabilities should be identified in the different TSO areas, using as a basis the ENTSO-E report [2-2].
2) Identify all capability options of converter-based generators that could satisfy these system needs and to provide commonly agreed definition about which of these capabilities fall under the "grid forming category". In doing so, the expert group shall describe the potential interactions with existing synchronous generation, based on experience and existing work. To prepare a consistent set of capabilities needed in future, the EG should provide the technical input for the capabilities needed to provide "steady state voltage control, fast reactive current injections, inertia for local grid stability, short-circuit current, black start and island operation" paralleling ENTSO-E and national market design/CEP implementation discussions.
3) Provide an overview on the technology readiness level of the capabilities of power park modules, HVDC-Systems, electricity storage modules and other relevant equipment (such as FACTs / STATCOMs / Grid Booster/etc …).
4) Analyse the possible impact of the technology on distribution networks and their readiness, considering the network architecture and the inherent operational criteria, as well as the regulation framework and the existing technical standards (in particular those regarding safety).
5) Finally, the connection network codes serve as a platform for the description and harmonization of capabilities. The fourth objective of this expert group is to clarify the technical description of such capabilities and recommend their inclusion in the relevant articles of the connection network codes (NC RfG, NC HVDC and NC DC) which will be needed in future power. As provided in the NC RfG today, the recommendations regarding the relevant articles in the NC RfG shall include a classification whether the capabilities can be optional or should be mandatory for Power Generating Modules and Electricity Storage Modules

The methodology taken by this expert group is to first review relevant regulations and existing results from relevant work groups and then harmonize advanced capabilities for future system needs based on these inputs and recent technological development.

2.2 Relevant regulations

The expert group has analysed gaps in the following regulations with respect to the subject on system needs of power systems with high share of PPMs and advanced capabilities,

- Commission Regulation (EU) 2016/631 (NC RfG)
- Commission Regulation (EU) 2016/1447 (NC HVDC)
- Commission Regulation (EU) 2016/1388 (NC DC)

It is clear that the established regulations do not directly address this subject, and there is urgent need to address advanced capabilities in future amendments of the grid codes.

2.3 Review on previous work on grid forming capabilities

This section first gives a broad overview on relevant pre-standardization efforts and research works worldwide. Then a detailed review of the most relevant work in the European context is given to lay the groundwork for making recommendations to the European connection network codes.

2.3.1 Overview on Grid forming worldwide

Table 1 gives a non-exhaustive list of pre-standardization efforts at national and/or international level, addressing system needs with high share of PPMs and grid forming converters. From this review, it is apparent that maintaining system stability is a worldwide challenge, particularly for nations with less interconnections to large power systems, such as Australia and Great Britain. There is a worldwide need to understand future power system needs with high share of PPMs and to address advanced capabilities with grid forming technologies.

Table 1: Overview (non-exhaustive) of pre-standardization efforts

Entity	Region/ Country	Report/Publication/Topic	Main results	Year
ENTSO-E	EU	High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters [2-2]	Overview of system needs and open questions of grid forming capability	2020
NERC	USA	Grid forming technology bulk power system reliability considerations [2-10]	White Paper on Grid Forming Controls focusing on reliability and stability of the system	2021
VDE FNN	DE	Guideline - grid forming & system-supporting behaviour of power generating modules [2-5]	Grid code requirements on grid forming	2021
AEMO	AU	Application of advanced grid-scale inverters in the NEM [2-11]	White paper providing recommendations for enabling grid forming technology	2021
GPST	Worldwide	System Needs and Services for Systems with High IBR Penetration [2-12]	Discuses system needs and readiness of IBR	2021
NGESO	GB	GC0137: Minimum Specification Required for Provision of GB Grid Forming Capability [2-4]	Grid code requirements on grid forming	2022
UNIFI	USA	Specifications for Grid forming Inverter-based Resources [2-13]	Requirements for grid forming inverters to achieve vendor-agnostic operation at any scale	2022
German TSOs	DE	4-TSO paper requirements for Grid Forming Converters [2-3]	Position paper on grid forming requirements	2022
CENELEC TC8X/WG03 Requirements	EU	Questions regarding the integration of voltage source generators on the distribution network [2-6]	Highlights open points of grid forming application in distribution grids	2022

Entity	Region/ Country	Report/Publication/Topic	Main results	Year
for connection of generators to distribution networks (50549 family Standard)				
CENELEC TC8X/WG03 (50549 family Standard)	EU	EN 50549-1: Requirements for generating plants to be connected in parallel with distribution networks - Part 1: Connection to a LV distribution network - Generating plants up to and including Type B [2-14]		2019
		EN 50549-2: Requirements for generating plants to be connected in parallel with distribution networks - Part 2: Connection to a MV distribution network - Generating plants up to and including Type B [2-15]		2019
		EN 50549-10: Requirements for generating plants to be connected in parallel with distribution networks - Part 10: Tests for conformity assessment of generating units [2-16]		2022
ESIG	Worldwide	Grid forming Technology in Energy Systems Integration [2-17]	Discuses global experiences in formulating grid forming requirements, characterization and testing of grid forming IBRs, and the key modelling and simulation tools	2022

In addition to the literature review, this expert group also had technical exchanges and fruitful discussions with leading research institutions working on grid forming controls. A short summary is given as following:

- 13.05.2022/Martin Schmieg, “VDE FNN Expert Network Grid forming & system-supporting behaviour of power-generating modules”, Mr. Schmieg presented main results on requirements of grid forming behaviour in addressing challenges in relation to energy perspective of future systems, particularly focusing on grid stability and system split.
- 16.09.2022/ Vincent Gabion, CENELEC TC8X WG03, “. Advanced Capabilities for Grids with High

  Shares of Power Park Modules Questions regarding the integration of voltage source generators on the distribution network “: Mr. Gabrion highlighted the open questions regarding mass introduction of grid forming controlled voltage source converters to the distribution system, particularly on stability, interaction with transmission system, interaction with online tap changers, protection and islanding. Presentation regarding CENELEC TC8X WG03 document „Questions regarding the integration of voltage source generators on the distribution network” 2022-09-15. Supported and integrated with the presentation “Advanced capabilities for System Stability. Impacts on DSOs’ open points final version” from Cerretti Alberto, Gabrion Vincent and Schaupp Thomas.
- 17.11.2022/Roland Singer, “Outcomes of the Research Project VerbundnetzStabil and an Approach for GFC-Testing” and “Type testing of GFC”: Mr. Singer shared main results on grid forming requirements and novel grey-box simulation approach when including grid

forming converters in large-scale transmission and distribution systems, and the procedures for type testing of grid forming converters developed at Fraunhofer.

- 16.02.2023/Prof. Marco Liserre and Prof. Mario Paolone. Grid Forming Converters potential and challenges. Grid Forming Converters are more stable in weak grids, react better in case of faults, offer damping and reliable provision inertial response. Furthermore, they can be straightforward integrated into scheduling frameworks capable to provide multiple ancillary services. All these elements contribute to increase the grid hosting capacity of non synchronous generation based on renewables. Challenges arise in how to quantify the damping and stabilization contribution of GFM and which tools shall be used to study stability of modern electric grids characterized by use of GFM. Also the impact of GFM in distribution grids in terms of possible unwanted islands or on protection shall be still systematically studied.

2.3.2 Review of pre-standardization efforts at European level

2.3.2.1 ENTSO-E Technical Group, “High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters”

This technical report was supported by ENTSO-E, WindEurope, SolarPower Europe and T&D Europe. In this report, seven topics of concern have been highlighted due to low or inadequate supply of system inertia and short-circuit current:

1) creating system voltage,
2) contributing to fault level,
3) sink for harmonics,
4) sink for unbalance,
5) contribution to inertia,
6) system survival to allow effective operation of Low Frequency Demand Disconnection (LFDD) and
7) preventing adverse control interactions.

Three classes of PPMs, as shown in Table 2 have been defined in the ENTSO-E report, to address these system needs.

- Class 1 PPMs are only equipped with basic functions focusing on survival, and
- Class 2 PPMs can further provide supporting functions such as voltage control, frequency support, damping and fast fault current injection.
- Class 3 PPMs shall be capable of “*supporting the operation of the ac power system (from EHV to LV) under normal, disturbed and emergency states without having to rely on services from SGs (synchronous generators)*”.

Table 2: Three classes of PPMs addressing the system needs [2-2]

Class 1 **Basics PPM – with focus on survival**	**Class 2** **'Advanced Control' and additional capabilities on top of Class 1**	**Class 3** **Grid forming control capable of supporting system without relying on SG**
• Full frequency operating range • Full voltage operating range • Basic reactive controls – e.g. Unity Power Factor • LFSM-O • Complies with local power quality requirements (e.g. harmonics / unbalance current)	• Fault Ride-Through • Voltage control – steady state, dynamic and at P=0 • FSM and LFSM-U • Provides damping • Fast Fault Current Injection	• Creates system voltage • Contributes to Fault Level • Contributes to total system inertia • Supports system survival to allow effective operation of LFDD for rare system splits. • Controls act to prevent adverse control system interactions • Acts as a sink to counter harmonics & inter-harmonics in system voltage • Acts as a sink to counter unbalance in system voltage

2.3.2.2 CENELEC TC8X/WG03, "Requirements for connection of generators to distribution networks"

CENELEC TC8X WG03 has actively supported the expert group activity, not just limited to the definition of the new capabilities, but also including a deep investigation of the overall impact on the electric system including distribution networks, and the gaps, or open issues, that still to be resolved to allow a massive introduction of grid forming converter technology.

This to assure technical neutrality and to allow decision makers to have all the necessary elements for their evaluations.

Starting from the analysis of "Outcomes of the Research Project VerbundnetzStabil and an Approach for GFC-Testing" and "Type testing of GFC" from Fraunhofer and from outcomes of the OSMOSE project, issues for distribution networks have been identified that still remain to be solved, as well identifying situations where grid forming converters could be connected immediately.

The results of this analysis are:

- protection strategies and operational solutions are not mature enough, and detailed evaluations are not yet sufficient to allow for the simple, safe and cost effective generalized introduction en masse of grid forming inverters in MV and LV distribution networks of each EU Country.
- on the other hand grid forming inverters could be immediately connected to the HV/MV busbars (HV or MV through dedicated feeders), avoiding the unwanted impacts on the DSOs' grids.
- In addition, WG03 came to the following additional considerations:
    - further standardization is needed as grid forming functionalities are not yet defined in sufficient detail to allow an immediate implementation;
    - correct simulations based on shared digital model including all capabilities and their interactions and hierarchies need to be developed and verified;

  - grid forming features and functionalities should be defined in detail at the European level, allowing manufacturers to develop and test a limited number of products and for each RSO to be able to perform verified simulations.

Three dedicated documents have been defined and delivered to the EG:

- CENELEC TC8X WG03 – insertion of GFC on the distribution network
- Impact of GFC-Converter_on_Distribution grids
- Advanced capabilities for System Stability Impacts on DSOs_open points

Finally, to further support grid forming introduction and to speed the process, reducing possible delays due to standardization, a New Work Item Proposal was defined titled "CLC/TS 50549-20 - Requirements for generating plants to be connected in parallel with electrical networks - Part 20: Definitions and tests of the electrical characteristics of grid forming generating and storage units" as technical specification and proposed to CLC TC8X. The proposal was approved at National Committees on 2023-03-24 with 12 positive votes, 3 abstentions and only 1 negative vote. Kick-off meeting on 2023-04-27 under the coordination of Singer Roland.

2.3.3 National case studies

This section reviews grid codes and standardization efforts at a national level. Germany and Great Britain are given as national case studies since during the course of this working group, these two countries have pioneered establishing national grid codes regarding grid forming capabilities.

2.3.3.1 Germany

In Germany, two working groups led by German TSOs and VDE FNN, respectively, have investigated requirements on grid forming capabilities in the context of the German and European interconnected systems.

German TSOs, "4-TSO paper requirements for Grid Forming Converters"

Motivated by maintaining system stability, security and availability, the four German TSOs (50hertz, Amprion, TenneT and Transnet BW) have issued a joint paper on clarifying the requirements for grid forming converters. In this joint position paper, the mandatory capabilities for grid forming converters are "*creating system voltage analogous to the induced rotor voltage of synchronous generators, instantaneous short-circuit contribution, provision of electrical inertia within the design limits, preventing adverse control interaction and controller stability*". While limiting the contribution to harmonics, regulation of negative sequence and provision of additional electrical inertia by means of extended energy reserve are defined as capabilities which can be demanded if necessary. In addition, black start capability is defined as an optional feature for grid forming converters.

VDE FNN

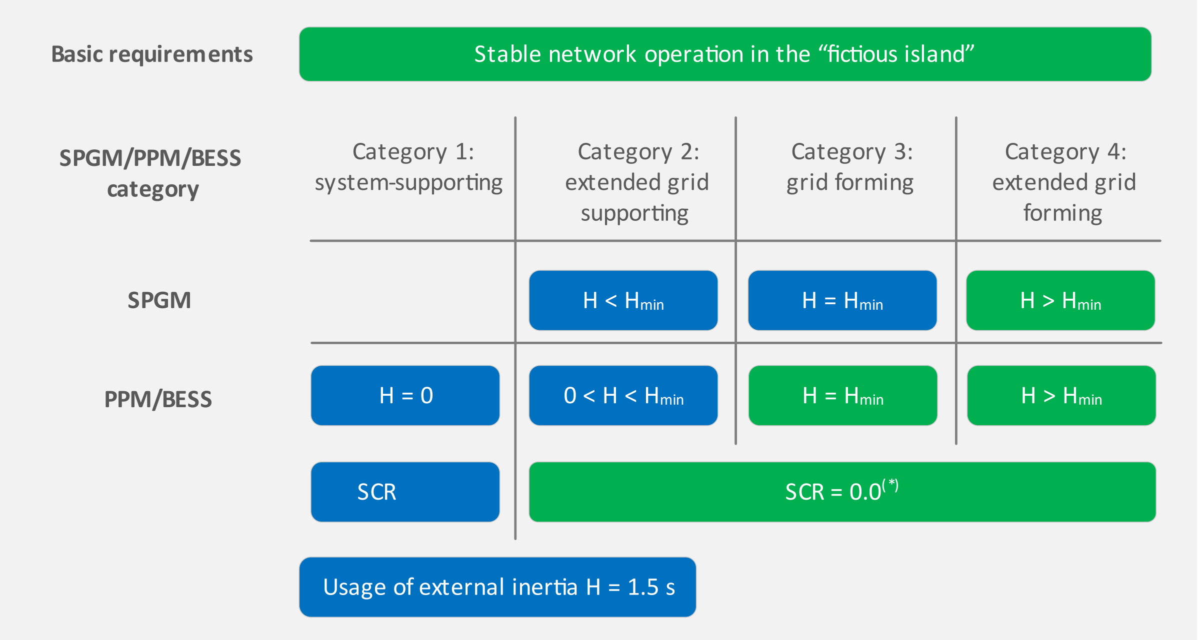
VDE FNN in collaboration with research institutes has issues reports on guidelines and test requirements of grid forming converters:

- "VDE FNN guideline - Grid-forming & system-supporting behaviour of power-generating modules"
- "VDE FNN Hinweis: Spannungseinprägendes Verhalten von HGÜ-Systemen und nichtsynchronen Erzeugungsanlagen mit Gleichstromanbindung"
- "VDE FNN Info: Future requirements for power system stability"

The VDE FNN approach identified "*separate network operability*" as a minimum requirement for a PPM in power systems with synchronous generators or pure inverter-based PPMs. In the VDE FNN guideline, the grid forming capabilities of a PPM is referred to "*the fundamental capability of* *maintaining a stable operating point with constant voltage and frequency during hypothetical standalone operation. Stability must also be maintained for defined disturbances with steady-state and dynamic deviations from the operating point*". The VDE FNN approach emphasizes the fundamental property of grid forming as being able to maintain both frequency and voltage stability in a fictious islanded operation. As such, power systems with grid forming PPMs would be capable of maintaining stable operation in interconnected systems and in case of system split.

Four categories of PGMs (including SPGM, PPM and BESS) are defined in the VDE FNN Info report:

- Category 1: System-supporting PGMs require the parallel operation of an SPGM which enables the PGM to stabilize active and reactive power balance when falling into the fictitious island and to operate in a stable manner with sufficient damping of the frequency and voltage control (HPPM = 0, SCR[1] ≥ 3, HSPGM = 1.5s, minimum SPGM/PGM-ratio = 30/70).
- Category 2: Extended system-supporting PGMs do not rely on external short circuit power (SCR = 0) but are not able to provide sufficient inertia to keep frequency and damping within defined limits ($0 < H^{2} < H_{min}$, SCR = 0, minimum SPGM/PGM-ratio = 30/70).
- Category 3: Grid forming PGMs are capable of controlling voltage and frequency in the fictitious island scenario without external support.
- Category 4: Extended grid forming PGMs provide an excess of inertia for the fictitious island scenario which helps to cope with system needs exceeding the fictitious island scenario and allows for system-supporting PGMs to operate in the fictitious island scenario.



Basic requirements	Stable network operation in the "fictious island"			
SPGM/PPM/BESS category	Category 1: system-supporting	Category 2: extended grid supporting	Category 3: grid forming	Category 4: extended grid forming
SPGM		$H < H_{min}$	$H = H_{min}$	$H > H_{min}$
PPM/BESS	$H = 0$	$0 < H < H_{min}$	$H = H_{min}$	$H > H_{min}$
	SCR	SCR = 0.0(*)		
	Usage of external inertia H = 1.5 s			

Figure 1 Classification of system-supporting and grid forming capabilities of PGM

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[1] Short circuit ratio

[2] The inertia constant (H) of a generator is defined as the ratio of kinetic energy stored at the synchronous speed ($\omega^{syn}m$) to the generator kVA or MVA rating.

2.3.3.2 GB

GB Grid code GC0137, “Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability”

The GC0137 work group, led by National Grid ESO with partners from wind turbine developers, HVDC manufacturers, developers, consultants, research institutes and interested parties, has focused on defining specifications for providing grid forming capabilities to the GB power system. The basic behaviour of a grid forming plant is defined as “*a voltage source behind an impedance, which is required to be capable of supplying: Active ROCOF Response Power, Active Phase Jump Power, Active Damping Power, Active Control Based Power, Control Based Reactive Power, Voltage Jump Reactive Power and Fast Fault Current Injection when subject to a network disturbance. These requirements also apply under both positive and negative frequency changes.”* GC0137 has identified three types of converters (Table 3):

- Conventional converter designs using PLL: the current state-of-the-art converter design which uses grid following control, which can provide limited grid supporting functions, such as damping power and contribution to faults.
- VSM0H (Grid Forming Static Power Converters with no inertia): provides “*the same capabilities as a synchronous machine are provided but the energy store (which would normally be reflected from the stored energy in the rotating mass of the drive train) is substantially reduced. This technology does however provide substantial benefits in providing of synchronising torque, fault infeed, limiting vector shift and helping to maintain a stable voltage profile during disturbed conditions*”.
- GBGFC – (GB Grid Forming Static Power Converter with Inertia): this type is defined as a full GB grid forming capability with an energy storage stability, which is capable of provide the same capabilities as a synchronous machine.

Table 3: GC0137 comparison of converter technologies [2-4]

Capability	GBGF-S	GBGFC	VSM0H	Conventional converter
Inertia power	Yes	Yes	Limited	No
Phase jump power	Yes	Yes	Yes	No
Damping power	Yes	Yes	Yes	Yes
Response (within one cycle)	Yes	Yes	Yes	No
Operate in synchronism with the system	Yes	Yes	Yes	No
Contribution to fault infeed	Yes - High	Yes	Yes	Limited/Slow
Bandwidth of controls system	< 5Hz	< 5Hz	> 5Hz	> 5Hz

2.4 Summary

Recent activities in grid forming converters clearly show that such functionality is of paramount importance in maintaining the stability of future power systems and power systems of different regions/voltage levels may have different needs when reaching a high share of PPMs. This report aims at harmonizing the fundamental system needs at high voltage (transmission) level, while highlighting the key differences from systems of medium/low (distribution) levels.

2.5 References

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[2-3] 50hertz, Amprion, TenneT, Transnet BW, "4-TSO Paper Requirements for Grid Forming Converters", 2022.

[2-4] GB Grid Code Modification GC0137 (Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability (formerly Virtual Synchronous Machine/VSM Capability) – available at https://www.nationalgrideso.com/industry-information/codes/grid-code-old/modifications/gc0137-minimum-specification-required, accessed 21-Nov-2022.

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[2-13] UNIFI consortium, "Specifications for grid-forming inverter-based resources," Technical Report, December 2022.

[2-14] CENELEC, "CENELEC - EN 50549-1 Requirements for generating plants to be connected in parallel with distribution networks - Part 1: Connection to a LV distribution network - Generating plants up to and including Type B", Standard, February 2019.

[2-15] CENELEC, "CENELEC - EN 50549-2 Requirements for generating plants to be connected in parallel with distribution networks - Part 2: Connection to a MV distribution network - Generating plants up to and including Type B", Standard, February 2019.

[2-16] CENELEC, "CENELEC - EN 50549-10 Requirements for generating plants to be connected in parallel with distribution networks - Part 10: Tests for conformity assessment of generating units", Standard, October 2022.

[2-17] Energy Systems Integration Group's High Share of Inverter-Based Generation Task Force, "Grid-Forming Technology in Energy Systems Integration", Technical Report, March 2022.

3 List of participants

Chair and vice-chairs:

- Hariram Subramanian, Solar Power Europe, Huawei
- Florentien Benedict, Expert Regulation at Stedin DSO, CEDEC.
- Mian Wang, Senior Consultant at Siemens Energy, Orgalim, representation since 09/2022
- Papiya Dattaray, Power Systems Advisor at Siemens Energy, Orgalim. Maternity leave since 09/2022

Changes in the list of participants:

- CEDEC had a withdrawal in their presentation.
- VGBE had both a withdrawal and an addition in their presentation.
- Orgalim had both a withdrawal and an addition in their representation.
- SmartEn had both a withdrawal and an addition in their representation.
- WindEurope had both a withdrawal and an addition in their representation.

over the duration of the EG.

Table 4: List of participants

	Full name	Member Organisation of GC ESC	Affiliation
1	Stanko Jankovic	ENTSO-E	TenneT
2	Hartmut Poppela	ENTSO-E	Amprion
3	Hans Abele	ENTSO-E	TransnetBW
4	Macarena Martín	ENTSO-E	REE
5	Adrian Gonzalez	ENTSO-E	ENTSO-E
6	Antony Johnson	external expert	National Grid ESO
7	Alberto Cerretti	CENELEC	ENEL S.P.A
8	Vincent GABRION	CENELEC	EDF
9	Thomas Schaupp	CENELEC	TransnetBW
10	Mike Kay	GEODE	ENA
11	Luca Guenzi	EUTurbines	Solar Turbines
12	Steffen Eckstein	EUTurbines	Siemens Energy
13	Maxime Buquet	EUTurbines	GE
14	Magdalena Kurz	EUTurbines	EUTurbines
15	Eckard Quitman	WindEurope	Enercon
16	Kamran Sharifabadi	WindEurope	Equinor
17	Rafael Portales	WindEurope	Hitachi Energy
	Vasiliki Klonari/	WindEurope	WindEurope
18	Vidushi Dembi	WindEurope	Windeurope
19	Giovanni Valtorta	EURELECTRIC	e-distribuzione

	Full name	Member Organisation of GC ESC	Affiliation
20	Pilar Nieto	EURELECTRIC	ENEL
21	Maria Avery	EURELECTRIC	ENEL
22	Santiago Gallego	EURELECTRIC	Iberdrola
23	Caoimhín Ó BRIAIN	EURELECTRIC	EURELECTRIC
24	Eric Dekinderen	VGBE	VGBE
	Ton Geraerds	VGBE	RWE
25	Klaus Oberhauser	VGBE	RWE
26	Simon Minett	COGEN Europe	Challoch Energy
27	Gunnar KAESTLE	COGEN Europe	B.KWK
28	Alfredo Rodriguez	COGEN Europe	Ingeteam Indar Machines
29	Alexandra Tudoroiu	COGEN Europe	COGEN Europe
30	Michal Kruszewski	COGEN Europe	PGE S.A
	Papiya Dattaray	Orgalim	Siemens Energy
31	Mian Wang	Orgalim	Siemens Energy
	Laurent Schmitt	SmartEn	Dcbel
32	Francois Colet	SmartEn	Dcbel
33	Andres Pinto-Bello	SmartEn	SmartEn
34	Martin Schmieg	external expert	VDE FNN/DIgSILENT
35	Paula Pernaut Leza	EASE	CENER
36	Fernando Morales	EASE	Highview Power
37	Selahattin Emin Umdu	EASE	Unda Engineering Inc
38	Florentien Benedict	CEDEC	Stedin
	Marc Malbrancke	CEDEC	CEDEC
39	Thorsten Bülo	SolarPower Europe	SMA Solar Technology AG
40	Hariram Subramanian	SolarPower Europe	Huawei
41	Thai Phuong Do	SolarPower Europe	CEA Ines
42	Adolfo Anta	SolarPower Europe	AIT
43	Georgios Antonopoulos	ACER	ACER

4 Timeline and course of meetings

In addition, the EG, through its chair, has updated the GC ESC at its 15 June 2022, 21 September 2022 and 30 November 2022 and 16 March 2023 meetings, send the preliminary version to ACER at 21 December 2022 presenting its preliminary draft results to the GC ESC on 6 April 2023.

The final draft report was prepared for submission to the GC ESC at the beginning of April 2023 for review and with a view to acknowledgement at June's 2023 GC ESC meeting.

The EG has met several times on the following dates:

Table 5: Meeting dates

Meeting dates	Number	TEAMS/in person
22 April 2022	I	Teams
19 May 2022	II	Teams
20 June 2022	III	Teams
8 July 2022	IV	Teams
16 September 2022	V	Teams
13 October 2022	V	Teams
17 November 2022	VII	Teams/in person
16 December 2022	VIII	Teams
19 January 2023	IX	Teams
16 February 2023	X	Teams
9 March 2023	XI	Teams
23 March 2023	XII	Teams

5 Terms and Definitions

For the purposes of this document the definitions and terms of NC RfG (EU 631/2016) and the following terms and definitions apply.

5.1

phase

instantaneous phase

ϑ

argument of the cosine function in the representation of a sinusoidal quantity

NOTE 1 The term "instantaneous phase" is only used when the independent variable is time.

NOTE 2 For the quantity $a(t)= \hat{A} \cos(\omega t + \vartheta 0)$, the phase is $\omega t + \vartheta 0$.

[SOURCE: IEV 103-07-04]

5.2

instantaneous frequency:

first derivative of instantaneous phase

5.3

rate of change of frequency

RoCoF

first derivative of instantaneous frequency or second derivative of instantaneous phase

5.4

phase jump

abrupt change in the AC voltage phase angle of an AC electrical network

5.5

phase jump power

active power that is injected or absorbed instantaneously by a grid forming unit in response to a phase jump at its terminals

NOTE The phase jump power resulting from a given event depends on the impedances between the internal voltage source of the power generation module and the mains voltage.

5.6

amplitude jump power

reactive power that is injected or absorbed instantaneously by a grid -forming unit in response to a change of AC voltage at its terminals

NOTE 1 In case of very low voltage dips only the provided current is of relevance.

NOTE 2 The amplitude jump power resulting from a given event depends on the impedances between the internal voltage source of the grid forming unit and the grid voltage.

NOTE 3 The amplitude jump power of a grid forming unit connected to the grid adds to the short circuit power at its point of connection.

5.7

inertia power

active power that is injected or absorbed by a grid forming unit in response to the RoCoF of the AC voltage at its terminals

NOTE The inertia power associated with a given event depends on the effective electrical inertia of the voltage source within the PGM as its frequency changes. In the case of a SPGM this inertia is associated directly with the mechanical inertia of the rotor.

5.8

electrical inertia

property of a grid forming unit such, that it maintains its frequency unless an active power imbalance occurs

5.9

instantaneous response <of a grid forming power park module>

response which is temporally co-incident with the changes in the electromagnetic forces creating the response

NOTE GB Grid forming in GC137 [6-1] currently defines the instantaneous response of a grid forming control to be faster than 5 ms.

5.10

point of connection

interface between the power generating module (PGM) and the power grid.

NOTE For the purpose of this document this is not necessarily equal to the legal definition of “connection point” as in NC RfG EU 631/2016.

5.11 Deviation relative to NC RfG (EU 2016/631) definitions

The terms synchronous generating module and power park module as defined in NC RfG are used in this report. In addition to the original definition, this report assumes the following provisions of the Phase II Final Report of the ESC EG Storage applicable. *“An electricity storage module connected to a network by a synchronous generator has to meet the same requirements as a synchronous power generating module and an electricity storage module connected to a network by a nonsynchronous generator or through power electronics has to meet the same requirements as a power park module (which could include electric vehicles).”*

6 System Needs that require advanced capabilities for grid stability

6.1 Need for new capabilities to maintain stability

The fulfilment of the European climate protection targets under the Green Deal will lead to a reduction in fossil fuelled synchronous generation capacity throughout Europe. Therefore, synchronous generation capacity will be replaced by converter-based generation (power park modules (PPM)) mainly full converter (FC) or double fed induction generator (DFIG)) to an increasing extent. The high share of non-synchronous generation in future energy transmission systems leads to a wide range of challenges concerning stability aspects. For example, conventional PPMs do not provide significant instantaneous power response to sudden active or reactive load changes in the grid, shifting this load to the remaining synchronous generators, which provide this response due to their short-circuit power (inherent voltage source behind an impedance characteristic) and the energy stored in their rotating mass which contributes inertia to the system. This leads to ever increasing RoCoF values and the risk of transient power imbalances. In general, secure grid operation and conceptual resolution of grid disturbances, with the increasing penetration on non-synchronous generation, are the superordinate and legally binding objectives of the transmission system operators (TSOs).

For obtaining stability, two preconditions have to be fulfilled:

1. An instantaneous compensation of a sudden imbalance of active and reactive power caused by a disturbance.
2. The stable and well-damped voltage and frequency behaviour of the system as a result of the stable and well-damped voltage and frequency control loops of the power generation modules.

Precondition 1) requires grid forming capabilities to provide phase jump power and amplitude jump power.

Precondition 2) requires inertia power as well as the appropriate design of the control loops for FSM, LFSM and voltage control.

The need for inertia power, phase jump and amplitude jump power damping as well as stability aspects regarding the power system are described in more detail in the following subclauses.

6.1.1 Phase jump power and amplitude jump power

Studies on voltage stability and short circuit current need have been conducted [6-2] [6-3] [6-4] showing that above a penetration of about 60% of grid following generation voltage stability is at risk. The provision of amplitude jump power as well as phase jump power with an instantaneous response is required, thus exceeding today's application of fast fault current injection. This is needed to:

- ensure instantaneous active power balance in case of load or generation changes,
- provide instantaneous short circuit current,
- provide harmonic and asymmetric load currents and
- provide sufficient voltage stability to allow for grid following inverters to operate.

Amplitude jump power must be provided instantaneously. Otherwise, if the provision is delayed, such as can occur with the present requirement to inject fast fault current within 30ms, the voltage stability could be lost within this time. This is resulting in a loss of synchronising torque.

6.1.2 Inertia power

In [6-5] the ENTSO-E Project Inertia Team quantifies the need for additional inertia. Without additional inertia, for all future grid scenarios of the central Europe synchronous zone that have been considered, there is a high number of possible system split situations that would lead to unmanageable RoCoF situations on both sides of the split line and therefore would lead to complete black out (global severe splits as introduced in [6-5]). The ENTSO-E Project Inertia Team proposes to provide additional inertia by renewable energies, electrical storage, as well as grid elements such as STATCOMs with inertia function [6-6], synchronous condensers, or market-based procurement. For the management of system splits as well as for normal operation, another effect of inertia power is crucial for the proper functioning of the frequency control in large electrical networks: The creation of a system frequency which is reflecting the actual mismatch of active power in the system. In order to achieve this, inertia power provided by power generation modules, including the inertia power provided by inverters, has to adapt the internal frequency depending on the active power exchange with the network by increasing its frequency in case of a decrease in active power provision and decreasing its frequency in case of an active power increase. Thus becoming able to synchronize and share power with other voltage sources, following the provision of phase jump power or inertia power.

According to [6-7], spatial distribution of the electrical inertia must be as equal as possible across the power system's area.

6.1.3 Stability

To ensure a stable power system operation, the provision of phase jump power and inertia power, together with the provision of FSM and LFSM must also operate in a stable manner. Equally, the provision of amplitude jump power together with the provision of voltage control must operate in a stable manner.

In case of a sudden network disturbance related to active power, the amount of inertia which is present in the system influences amongst other things the initial damping. The more electrical inertia, the more capacity for sufficient initial inertia power flow and thus a better damped frequency transition. Historically and up until today, particularly for distributed generation, stability issues are characterised by a relatively small generating facility operating in parallel with the much larger grid system, whose inertia dominates the small facility's behaviour. A change of the generated power will have no or little effect on the frequency (comparable to the behaviour of the power generation modules in open loop). This stability paradigm will change once a large share of connected power generation modules will behave in the same or in a similar way. A change in the voltage phase angle, frequency or voltage amplitude at the point of connection will result in an response in the generated power of the power generating module which again will cause an immediate change of the voltage phase angle, frequency or voltage amplitude at the point of connection (now comparable to the behaviour of the power generation module in closed loop). This can be seen as a feedback control loop of the system formed by the power generating module and the power system. As a large share of power generation modules behave in a similar way, the system behaviour of such a system can be simulated and modelled in a simplified way in which one power generation module supplies only a single load. In future power generating modules must operate stably under these conditions.

For FSM and LFSM this can be described as follows:

- In the case of network disturbances with an active power imbalance, the grid forming assets that are present in the network are providing phase jump power and with this are balancing the active power mismatch in the first instance. Due to the adaption of the internal frequency as described in 6.1.1 of the SPGMs and grid forming PPMs, the grid frequency is changing.
- For relatively small disturbances, leading to frequency deviations < ± 200 mHz, LFSM is not active. FSM is provided by a few power generating or storage modules. Thus, the active FSM power of the few FSM generating modules are added to the system balance to stabilize the frequency. The frequency change being damped by the total system inertia

which is a lot in a large system. This will ensure that the FSM stability condition is always fulfilled resulting in a good damping.

- For relatively large disturbances, leading to frequency deviations > ± 200mHz, all LFSM control loops are activated. This means that all generation is subject to its own control action, compared to FSM where only a small quantity of generation has a control action. Hence the ratio of inertia to active power control is much less in LFSM situations, leading to a dramatic reduction in effective damping. In a low inertial future, LFSM control loops will need careful design to cope with the lack of damping compared to the historical situation. The main reason for the damping effect of inertia is that it hinders the frequency being changed by a change of active power infeed of the PGM and therefore "opens" (to a certain extent) the control loop. This is not done by directly deactivating the feedback branch, but indirectly by keeping the frequency almost constant whilst changing the power output of the PGM. In the moment of activating all the LFSM controls, the frequency is significantly changed by the power in-feeds of the PGMs. This is equal to "closing" the loop.

Therefore, a closed loop setup representing the relevant grid disturbance scenarios to be considered shall be used when testing the stability of LFSM and voltage control loops and if applicable e.g. for converters the control loops for amplitude jump power, phase jump power and inertia power.

Besides the above stated stability issues, the robustness of a power generating module and each individual unit and component within, is vital for a stabile power generating system. Namely the robustness against overvoltage and undervoltage events as well as RoCoF and phase jump events must be ensured. Requirements regarding robustness have not been quantitatively discussed in this expert group as this discussion is already ongoing in GC-ESC view of the amendment process of NC RfG.

6.1.4 Protection and operational needs in distribution grids

System operation and protection of distribution networks are traditionally designed for distributing power from transmission level to the low voltage level. Today's distribution networks are not designed to have multiple grid forming voltage sources connected on low and medium voltage level. Further research and, in many cases, significant reconfiguration of the distribution grid may be needed to ensure safe and stable operation if generation providing inertia power, phase jump power, amplitude jump power, voltage regulation capabilities represents a significant share, or even exceeds, the local power consumption.

Technical concerns regard lack of real life feedback on potential stability issues of voltage source generators on utility networks (due to their resistivity and varying configurations), interaction with tap changers at the substation, reactive power exchange with transmission system and technical losses, behaviour during faults and interaction with protection and network automation, islanding risk with associated safety issues for persons (current absence of any coordinated and reliable protection in possible islands). So far neither detailed studies nor real scale demonstrators of a distribution system equipped with a significant share of grid forming generators have been performed and tested. So, we lack experience on the behaviour of the distribution networks and the modifications needed and currently lack any recognized common technical solutions.

As a consequence, a major concern is the financial impact of a massive growth of grid forming generation in distribution networks. Once the technical issues are clarified, a cost benefit analysis is needed to assess the modifications required to ensure a proper operation of distribution networks in comparison to the connection of grid forming assets to higher voltage levels.

As the full implications for DSO networks are still very uncertain pending further detailed research, it will be prudent to only allow negligible penetration of such technology into MV and LV networks for the time being. Integration of grid forming generation in LV grids and MV grids shall not be made compulsory by NC RfG but left to the recommendation of TSOs for agreement by national regulatory authorities (NRA) taking into account specific features of DSOs grids.

6.1.5 Further aspects

The provision of grid forming characteristics must also be evaluated based upon technology-specific limitations and costs involved. However, these considerations are out of the scope of this document.

Besides the new capabilities described in this clause, the mentioned stability aspects and closed loop evaluation are relevant for all grid support functions (e.g. reactive power control Q(U)). Future NC RfG and national NC RfG implementation should consider the need for increased focus on stability in the provision of support functions.

6.2 Basic characteristics of grid forming power park module

One technical approach to meet these future challenges of the changing generation structure is the use of PPM (FC as well as DFIG) and storage modules with grid forming characteristics.

In the recent past various studies on grid forming converters have been performed and the positions of TSOs have been published (e.g. [6-8]). The technical report HPoPEIPS (High Penetration of Power Electronic Interfaced Power Sources) of ENTSO-E [6-7] is probably one of the most important and best-known preliminary publications in Europe on the definition of the conceptual characteristics of grid forming converters. The report was published as part of the interdisciplinary cooperation between ENTSO-E and manufacturers' associations [6-7].

In order to ensure stable grid operation even with a high share of converter-based generation from 60% to 100%, the technical report HPoPEIPS [6-7] identifies basic characteristics of grid forming power generating modules, called grid forming capabilities. In principle, grid forming characteristics can be provided by all power generating modules (PGM) and storage modules with self-controlled grid converters or synchronous generators. This comprises synchronous as well as non-synchronous (converter-based) generation, and also fully integrated network components like HVDC links, STATCOM and synchronous condensers and loads. However, each of those technologies faces different technological boundary conditions regarding the extent of grid forming characteristics, that can be provided in a feasible manner. Chapter 8 of this report provides more insight on those aspects.

The following subsections of this chapter update and summarize characteristics of grid forming units considered necessary e.g. in PGMs or fully integrated network components to a sufficient share related to the installed power generating capacity in the power system in order to meet the needs discussed in section 6.1.

6.2.1 Creating system voltage and contribution to fault level

A grid forming converter behaves like a voltage source behind an impedance. The dynamics of the internal voltage magnitude and angle is limited and lags the grid dynamics.

As a consequence, stabilizing and equalizing currents occur between the grid voltage and the internal source voltage of the grid forming converter. In the event of a short circuit (step change in voltage), this current contributes to the short-circuit current. In the event of a phase jump, this current contributes to a phase jump power. The dynamic, the phase position and the amplitude of the short-circuit current contribution, are determined by the effective converter impedance, grid impedance and fault impedance. Fast current limitation prevents currents above rated values − e.g. in the event of faults with low residual voltage (short circuit close to the converter station). The current and power limitation is designed in a way to maintain synchronism.

Set points for active and reactive power are tracked by adjusting the voltage source behind an internal impedance with a defined slow dynamic. The generating unit manufacturer will define the dynamic of the adjustment. It should be possible to configure the temporal parameters of this dynamic adjustment to respect the needs of the local point of connection. This is focused on the voltage control behaviour and inertia power if provided.

An analogy to a synchronous machine does not imply that the control behaviour of the grid forming converter reflects the equation of motion of a synchronous machine.

6.2.2 Provision of electrical inertia (Contribution to Inertia) within the design limits:

The internal voltage's frequency behaviour following an active power unbalance is proportional to this active power unbalance after a finite time. This active power unbalance may be caused by a step change of the grid voltage phase angle or by a ramp change of the grid frequency. This change of active power is analogous to the effect of inertia characterised by the time constant of synchronous machines.

A fast current and power limitation protects the power-generating facility, e.g. in case of major disturbances, which would lead to a supply of power outside the design limits or an excessive charge/discharge of the inherent energy storage. The current and power limitation is designed to allow synchronism to be maintained.

The maximum energy that can be exchanged with the connected grid is limited by the inherent energy storage capability of the power-generating facility's components. (Extended provision of inertia by a dedicated energy storage is described in 6.3.2.).

Asymmetric power change capability, ie available in only the positive or negative direction, may be applied in order to extend the inertia power provided to the system in the case of a grid event demanding for that direction (e.g. power reduction for renewable energies, or charging reduction in the case of loads with internal energy storage such as EV).

The behaviour described causes the voltage provided by the converter to synchronize with the grid voltage in its phase angle and frequency with a certain inertia. This behaviour limits the frequency of the system in the RoCoF and adjusts the frequency proportionally to the power imbalance at the same time. This ensures that higher-level emergency functions (e.g. the frequency-dependent load shedding LFDD or LFSM-O) take effect as designed in the case of a significant active power imbalance.

6.2.3 Stability of Control

The control of a grid forming power-generating facility and of grid forming HVDC systems that connect power park modules to a transmission or distribution grid must be stable. Any change of phase, frequency or voltage at the point of connection will result in an immediate response in the generated power of the power generating facility which again will cause an immediate change of phase, frequency or voltage at the point of connection; consequently the stability must be evaluated in a system that reflects the directly closed loop between the power system and the power generating facility. One individual power generating facility can be considered stable according to this principle, if the power generating facility is able to operate without any further source of short circuit power and with no, or only a defined and limited additional source of inertia. This concept must be applied for all advanced capabilities, the provision of amplitude jump power, phase jump power, inertia power, FSM and LFSM.

6.3 Other characteristics of grid forming converters

In the following, with reference to the HPoPEIPS report [6-7], the characteristics of grid forming converters are listed which can be demanded by the TSO if technically feasible for the considered technology and necessary from a grid planning point of view.

6.3.1 Harmonics and negative, zero sequence

In principle, according to chapter 6.2, grid forming converters are designed in such a way that the resulting converter impedance has a positive real part for frequency components not equal to 50 Hz and for the negative and zero sequence.

Depending on the control structure additional control of specific frequencies or negative and zero sequence components are possible and may be provided.

6.3.2 Provision of additional electrical inertia (Contribution to Inertia) by means of extended energy reserve:

In addition to the requirements according to 6.2.2, additional energy storage can be provided. The maximum energy that can be exchanged with the connected grid can be taken from this dedicated energy storage, extending the inertia capability of the power-generating facility. Thus, the grid forming controlled power generation facility is able to provide a constant inertia even for events that reach the frequency limits of the operating range.

6.4 Characteristics needed for the operational network codes

The characteristics needed in the abnormal state of the grid (see SOGL Art. 18) have to be analysed in a system where the majority PGMs are PPMs in order to fulfil the obligations in the System Defence Plan (SDP) and System Restoration Plan (SRP) in accordance with the NC E&R.

The impact on PPMs of the following topics has to be evaluated in this additional analysis:

- Modification of active or reactive power as imposed by the TSO (called remedial actions).
- Obligation to implement the additional national measures as defined in the SDP and the SRP
- If specified in the SRP for each PPM, the auxiliary supply and SCADA systems must be able to withstand a blackout of 24 hours or more.
- According to the current version of NC RfG, black start is not mandatory but most TSOs prefer a geographical distribution of black start units. Will this exemption continue to exist in the future?
- Any plant providing black start must have grid forming capabilities (including SPGMs).
- Methods to reduce the inrush currents of transformers, overhead lines and cables (MV & HV)
- Strategies and methods to create islands with generation and load by energising grid installations and respecting the imposed frequency and voltage ranges (47.5 Hz – 51.5 Hz and ± 10% U_{nom})
- Synchronisation (at HV and MV) of energised islands by modifying the frequency and voltage
- etc.

The expert group sees the solution of all those topics as a subject for a future ENTSO-E forum in order to ensure that relevant experts in restoration issues and owners and operators of SPGMs, synchronous condensers or static VAR compensators are appropriately consulted on these issues. Chapter 8 of this paper gives an overview of expected problems for each technology.

6.5 Gap Analysis of Connection Codes

In the current NC RfG some aspects regarding robustness are covered. Namely undervoltage ride through in Article 14 (3) and RoCoF immunity in Article 13 (1)(b). All other aspects identified in this chapter are not present in NC RfG and should be added in the upcoming revision:

- Robustness to overvoltage (overvoltage ride through),
- Robustness to phase jumps,
- Provision of amplitude jump power,
- Provision of phase jump power,
- Provision of inertia power,
- Evaluation of control stability in a closed loop setup.

Regarding undervoltage ride through in Article 14(3) it is pointed out, as the GC-ESC Expert Group Baseline for type A PGMs concluded in its report, that this requirement should be applied in Article 13 for Type A power generating modules for several generating technologies.

Chapter 10 and Chapter 11 provide additional information on how to close these gaps.

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7 Potential issues on distribution networks as a consequence of a massive penetration of grid forming converters on MV and LV networks

The aim of this chapter is to list and describe the critical issues regarding the high penetration of grid forming converters into distribution networks if sufficient time is not allowed to design appropriate accommodations into those networks.

This new technology is certainly needed for the transmission system, but nevertheless the downsides for distribution networks are not yet fully known.

It must be noted that DSOs have technically distinct networks with specific operational criteria, which are also defined by national Regulation Acts from member states' governments or NRAs.

The more sophisticated the network operation, the greater the impacts and, therefore, the greater the technical and economical efforts to adapt the network to significant penetration of grid forming converters.

A complete evaluation is not yet available of the overall accommodations that would allow for a simple, safe and cost effective introduction of grid forming inverters on MV and LV distribution networks in each EU Country in a generalized way and in a relatively short time.

It is not only a matter of the timing (or costs) of simulations and analyses, but is also the absence of a sufficiently complete set of standards for grid forming converters, defining the details of the different functionalities and their interactions, which is one of the main obstacles in performing the necessary feasibility studies.

In the table below are highlighted most of the critical points regarding the use of grid forming converters in the current networks and some mitigations are listed.

Table 6: Potential Issues on distribution networks

Topic	Issue	Safety for persons impacted	Treatment
Stability of a power system provided by generators connected to MV and/or LV networks	The power system is currently stabilized by synchronous generators connected to the transmission system. They synchronize properly together thanks to the predominantly reactive nature of transmission lines. The distribution network is much more resistive than the transmission system. Adaptations are at least needed in the control of generators (virtual impedance?) to ensure stability of generators. No real size demonstrator (for instance on the MV/LV network downstream of a HV/MV substation) has been made so far to show the proper operation of massive penetration of grid forming converters on a real distribution network (in particular regarding stability issues). Experience gathered on microgrids is useful, but not at all sufficient for distribution lines that can reach tens of km (up to 100 km in some cases) and on existing networks that have not been designed from scratch to be supplied by grid forming converters and whose configurations are usually much more variable over time with respect to transmission ones.	No	Grid forming digital models including all features and their hierarchy are not available, as no Standardization exists. Very basic grid forming models are available in the standard library of most commonly used simulation software, which are not at all elaborated to the required full functionality. This has to do with the following aspects: • There are not yet widely defined and accepted functionalities as they are currently being worked on. • “Ready to use” models may be available, but they are manufacturer models, therefore subjected to confidentiality agreements. • More sophisticated applications which involve the real control code are on a project level. In addition, real size demonstrators on real distribution networks with different operational criteria should be made to show the proper operation with the massive penetration of grid forming converters.
Unintentional islanding	Grid forming operation will significantly increase the risk of unintentional islanding as it is the very purpose of grid forming to stabilize voltage and frequency. At present, fault detection and clearing for unplanned islands is not present on MV and/or LV networks. Islands are	Yes	Grid forming should not be installed on LV networks. At present, only transfer tripping or similar solutions could be effective, but the number of LV connected generators is extremely high to consider such a solution applicable. In some countries, the latency times will be an issue, and cyber security issues will be an issue everywhere.

Topic	Issue	Safety for persons impacted	Treatment
	usually random in nature, having location, extent and timing depending mainly on faults. Unintentional islanding may induce damage on equipment (out of phase reclosing, fires due to overcurrents not correctly cleared), but, most importantly, may lead to undetected earth faults with an associated risk for persons. Depending on the DSO’s system automation, unintended islands may delay the restoration of supplies to customers affected by DSO system faults. This problem is especially acute with generation connected to the LV network as this generation does not detect earth faults on the MV network. The protection systems in customers’ installations may not operate correctly because of the higher than expected source impedance during islanding. Resynchronization issue are not at all considered at present. Dealing with the issue requires to modify the protection and/or communication scheme, and possibly switchgear, with high costs and lead times associated		The possibility of grid forming on the MV network needs to be studied on a case-by-case basis, taking into account specific operational criteria of the networks. If grid forming is installed with as a consequence an unacceptable increase in the risk for persons, the only viable solution is a costly modification of the protection and/or communication scheme. Such approaches are not yet defined and will not be trivial to implement considering the state of art of Standardized solutions and devices, except for transfer tripping, whose applicability is costly and whose technical limits have to be clarified. No advanced research or pilot implementations are available which consider random islands similar to those which would be present on distribution networks.
Interaction with tap changers Reactive power exchange with transmission	Onload Tap Changers (OLTC) installed at a substation are aimed at maintaining a stable voltage on the network as are grid forming converters. The interaction between these must be checked. Note also that voltage is often the main limitation in connecting additional capacity to distribution networks, and therefore OLTCs are now being installed by DSOs on MV/LV transformers.	No	At a minimum, detailed simulations should be performed. But grid forming standardized models are not available, any Standardization being currently absent. Real size demonstration on a real distribution network would also be necessary following the simulations.

Topic	Issue	Safety for persons impacted	Treatment
system and limitation of technical losses	The effect on reactive power exchange between the distribution and transmission systems, and the effect on technical losses, should also be studied.		
Operation of protection and automation systems	There is a need to guarantee proper operation of protection and automation systems to discriminate correctly all faults on the networks, and not compromising the continuity of supply performance required by regulatory frameworks (i.e. fault clearance and automatic supply restoration of healthy sections, upstream and downstream from the faulted one). Refence parameters for quality of supply regulations and commercial contracts are based on existing Standards. The proper operation of the protection for fault currents supplied exclusively by power electronics on the distribution network needs to be checked.	Yes	A real size demonstrator on a real distribution network should be used to show the proper operation of protection with a massive penetration of grid forming converters. Digital simulations are not enough as there is not yet any Standardized grid forming model. There are many ways to implement control modes for grid forming, and equipment may behave in various ways in fault conditions and hence simulations may not capture all real-life phenomena.
Interface protection relays (IPRs)	IPRs are Standardized and aimed to disconnect generators from the grid in case of faults on the grid itself. IPRs sensitivity has been already reduced and operation times enlarged to allow grid-following inverters to stay connected and operate within the limits required from RfG 1.0. Further modification may be needed with grid forming, to be completely evaluated (maybe IPRs should be removed).	Yes	Grid forming functionalities being not yet standardized and digital models, therefore, not available, any preliminary analysis on IPRs is not possible.

Designing a DSO system to include grid forming converters is not possible yet as precise definitions of grid forming requirements and an appropriate framework or hierarchy for those requirements has not been developed. Initial standardization of the requirements (as proposed in the rest of this document) needs to be undertaken.

System analysis using appropriate models of grid forming devices that take into account the different operational criteria of DSOs' networks (and their regulatory frameworks) are urgently needed, followed by pilots and actual field demonstrators.

As this is a European problem, grid forming features and functionalities should be defined in detail at the European level, not national, allowing manufacturers to develop and test a limited number of products and for each relevant system operator (RSO) to be able to perform verified simulations.

Except for pre-planned situations where islanding is intentional and therefore a main design element, it should be avoided. Advantages that result from intentional islanding are currently very limited with very high costs and safety risks. This is a particular issue for grid forming generation connected at LV which could sustain an MV island.

Where islanding could be managed or would still be easy to detect and shut down (e.g. grid forming connected directly to HV substation busbars or to a MV busbar through dedicated feeders with no load), the inclusion of grid forming generation can be accommodated without further delay following the creation of appropriate standards.

8 Which technologies can provide grid forming capabilities?

8.1 Introduction

In this chapter, an overview on relevant technologies is provided, which will play a major role in the future electric power system. In Annex A1, for each technology, more background on the general design approach, technical boundary conditions and specific characteristics are described and the modification need for providing additional system capabilities is outlined. This assessment has been done by the stakeholders themselves. It should be taken into account that potential capabilities, which have yet not been widely explored and therefore have low technology readiness, can be assessed only on a very high level and with a certain degree of uncertainty. Therefore, additional risks may arise or current challenges may be solved in the future. The technologies considered here are PGMs, as well as non-PGM appliances.

The Annex A1 also comprises a description on control capabilities of inverter based devices and a section on potential contribution of converter based technologies during black start and grid restoration.

Historically, with appropriate controls SPGMs provided the capabilities needed. The electric power system works well even with a certain level of non-synchronous generating facilities. Depending on the reference scenarios, the system needs outlined in chapter 6 can be covered by providing the capabilities to a sufficient extent on the one hand and an appropriate level of robustness of the PPMs on the other. Thus, not necessarily all new power generating modules need to provide all capabilities, where there are sufficient other technologies and appliances which can provide them. Therefore, it is important to know the specific characteristics of each technology, in order to evaluate which ones are more suited to contribute to fulfilling system needs. It is also necessary to decide the technical and market related regulatory strategies for an energy transition which appropriately balances system stability overall with individual stakeholders' costs.

The system needs which are related to those identified in chapter 6 are as follows:

1) Need for new capabilities to maintain stability
    a. Phase jump power and amplitude jump power
    b. Inertia power
    c. Stability regarding FSM, LFSM and voltage control loops
2) Protection and operational needs in Distribution grids
    a. Basic characteristics of grid forming power park module:
    b. Behaving like a voltage source behind an impedance (resulting in grid stabilizing currents between the grid voltage and the PPM's internal source voltage; current limitation is designed to maintain synchronism)
    c. Provision of electrical inertia within the design limits, current and power limitation is designed to maintain synchronism; additional electrical inertia might be provided by a dedicated energy storage
3) Characteristics required by the Operational Network Codes
    a. The characteristics needed in an abnormal state of the grid (see SOGL Art. 18) have to be analysed in a system with a majority of PPMs.

8.2 Overview on technology specific capabilities

In the following table, for the technologies described in Annex A1 the possible capabilities to contribute to the system needs identified in chapter 6 are summarized in a roughly quantified way ("low-medium-high" for comparison between the technologies) considering their usual inherent hardware characteristics. For each system need and technology the main limiting factors and dominating boundary criteria that have an impact on the capability are listed. Finally, the major measures required if the capability is to be provided at least to a minimum extent are listed.

For all converter-based technologies it is assumed that a "Voltage Source behind Impedance" / grid forming-Control could be successfully applied, even though today the technology readiness is yet very low for some technologies in this regard.

Table 7: Phase Jump Power / Energy

Phase Jump Power / Energy				
	positive (negative phase angle change)		*negative (positive phase angle change)*	
	Capability, boundary criteria and limiting factors	*Needed measures to utilize the capability*	*Capability, boundary criteria and limiting factors*	*Needed measures to utilize the capability*
HVDC	***medium*** **Range**$^{1)}$ - limited by thermal stress of semiconductors (in case of an operating point providing active power) - depends on operating point before the event - limited by the size of DC-link energy **Performance** - depending on control (damping etc.)	First products available on the market	***medium*** **Range**$^{1)}$ - limited by thermal stress of semiconductors (in case of an operating point consuming active power) - depends on operating point before the event - limited by the size of DC-link energy **Performance** - depending on control (damping etc.)	First products available on the market
Statcoms	***low*** **Range**$^{1)}$ - limited by thermal stress of semi-conductors; - limited by the size of DC-link energy; - depending on loading before the event - no primary power source; **Performance** - depending on control (damping etc.)	First products available on the market	***low*** **Range**$^{1)}$ - limited by thermal stress of semi-conductors; - limited by the size of DC-link energy; - depends on loading before the event - no primary power source **Performance** - depending on control (damping etc.)	First products available on the market

Phase Jump Power / Energy				
	positive (negative phase angle change)		*negative (positive phase angle change)*	
	Capability, boundary criteria and limiting factors	*Needed measures to utilize the capability*	*Capability, boundary criteria and limiting factors*	*Needed measures to utilize the capability*
PV	***Low*** **Range**[1)] - limited by thermal stress of semiconductors - limited by the size of DC-link energy - depends on loading before the event **Performance** - depending on control (damping etc.)	Fundamental re-engineering of Software/Control incl. protection Additional storage capacity needed for phase jump energy	***low*** **Range**[1)] - depending on converter structure limited by the size of DC-link energy - depends on loading before the event **Performance** - depending on control (damping etc.)	Fundamental re-engineering of Software/Control incl. protection Additional storage capacity may be needed for phase jump energy
Wind Type IV	***low*** **Range**[1)] - limited by thermal stress of semiconductors - depends on loading before the event - limited by mechanical load restrictions - limited by the size of DC-link energy **Performance** - depending on control (damping etc.)	Fundamental re-engineering of Software/Control incl. protection Additional storage capacity needed for phase jump energy Strengthening of mechanical components	***low*** **Range**[1)] - depending on loading (and rotor speed) before the event - limited by mechanical load restrictions - limited by the size of DC-link energy; - limited by chopper capacity **Performance** - depending on control (damping etc.)	Fundamental re-engineering of Software/Control incl. protection Additional storage capacity and/or Strengthening of mechanical components Additional chopper capacity (if applicable) needed for phase jump energy
Wind Type III	***low*** **Range**[1)] - limited by thermal stress of semiconductors - depends on loading and rotor speed before the event	Fundamental re-engineering of software/control incl. protection Additional storage capacity needed for phase jump energy	***medium*** **Range**[1)] - limited by thermal stress of semiconductors - depending on loading and rotor speed before the event **Performance**	Fundamental re-engineering of software/control incl. protection Additional storage capacity or stronger drive train needed for limiting impact to turbine lifetime

Phase Jump Power / Energy				
	positive (negative phase angle change)		*negative (positive phase angle change)*	
	Capability, boundary criteria and limiting factors	*Needed measures to utilize the capability*	*Capability, boundary criteria and limiting factors*	*Needed measures to utilize the capability*
	- limited by mechanical load restrictions - available energy storage (DC-link) very small **Performance** - depending on control (damping etc.)		- depending on control (damping etc.)	Additional chopper capacity (if applicable)
BESS	***medium*** **Range**[1)] - limited by thermal stress of semiconductors (in case of an operating point providing active power) - depends on loading before the event **Performance** - depending on control (damping etc.)	First products available on the market	***medium*** **Range**[1)] - limited by thermal stress of semiconductors (in case of an operating point consuming active power) - depending on loading before the event **Performance** - depending on control (damping etc.)	First products available on the market
Synchronous Condensers	***high*** **Range**[1)] - the synchronous condenser has high pole slip limits (total angle reserve) **Performance** - damping provided by design	none	***high*** - limited by impedance and pole slip limits **Performance** - damping provided by design	none
SPGM	***high***	none	***high***	none
[1)] Amplitude / Energy				

Table 8: Inertia Power

Inertia Power				
	positive		*negative*	
	Capability, boundary criteria and limiting factors	*Needed measures to utilize the capability*	*Capability, boundary criteria and limiting factors*	*Needed measures to utilize the capability*
HVDC	***low/medium*** **Range**1) - limitations due to semiconductors - limitations due to primary source (offshore wind / interconnector)	First products available on the market	***medium*** **Range**1) - limitations depending on operating point	First products available on the market
Statcoms	***none*** **Range**1) - more possible (by design), if there is enough DC-Link storage ("E-Statcom")	First products available on the market Additional storage capacity needed for inertia energy (usually orders of magnitudes, depending on grid code requirements)	***none*** **Range**1) - more (by design), if there is enough DC-Link storage	First products available on the market Additional storage capacity needed for inertia energy (usually orders of magnitudes, depending on grid code requirements)
PV	***none*** **Range**1) - unless operating in curtailed mode	Fundamental re-engineering of software/control incl. protection Additional storage capacity needed for inertia energy (usually orders of magnitudes, depending on grid code requirements)	***medium*** **Range**1) - limitations depending on operating point	Fundamental re-engineering of software/control incl. protection Hardware: additional storage capacity may be needed for stability
Wind Type IV	***low,*** **Range**1) - limitations due to thermal stress of semiconductors and stably extractable energy from the rotor (performance) - depends on loading and rotor speed before the event - available energy storage (DC-link) very small	Fundamental re-engineering of software/control incl. protection Stronger drive train if no storage is added Additional storage capacity needed depending on the grid code requirements	***medium*** **Range**1) - depending on loading and rotor speed before the event - limitations due to thermal stress of semiconductors - available energy storage (DC-link) very small - limited by mechanical load restrictions	Fundamental re-engineering of software/control incl. protection Stronger drive train if no storage is added Additional chopper capacity (if applicable) as an alternative to storage to limit impact on turbine lifetime.

Inertia Power				
	positive		*negative*	
	Capability, boundary criteria and limiting factors	*Needed measures to utilize the capability*	*Capability, boundary criteria and limiting factors*	*Needed measures to utilize the capability*
	- limited by mechanical load restrictions - risk of stalling - capability none, if seamless transition from phase jump power to inertia is expected		- limited by chopper capacity (if applied)	
Wind Type III	***low*** **Range[1)]** - limitations due to thermal stress of semiconductors and stably extractable energy from the rotor (performance) - depending on loading and rotor speed before the event - available energy storage (DC-link) very small - limited by mechanical load restrictions - risk of stalling	Fundamental re-engineering of software/control incl. protection Potentially higher stress on drive train if no storage is added Additional storage capacity needed depending on the grid code requirements	***medium*** **Range[1)]** - depending on loading and rotor speed before the event - limitations due to thermal stress of semiconductors - available energy storage (DC-link) very small - limited by mechanical load restrictions - limited by chopper capacity (if applied)	Fundamental re-engineering of software/control incl. protection Additional chopper capacity (if applicable) or stronger drive train to limit impact on turbine lifetime.
BESS	***medium*** **Range[1)]** - limited by thermal stress of semiconductors - limitations due to battery power limitation (overload capability)	First products available on the market	***medium*** **Range[1)]** - limited by thermal stress of semiconductors - limitations due to battery power limitation (overload capability)	First products available on the market
Syncons	***high*** **Range[1)]** - Impact on high mechanical losses	adding flywheel	***high*** **Range[1)]**	adding flywheel
SPGM	***high*** **Range[1)]** - limitations?	adding flywheel	***high*** **Range[1)]** - limitations?	adding flywheel

Regarding the classification of LFSM stability it is assumed that there is enough primary active power ("headroom") available. All technologies tend to be operated at maximum available power. The capability outlined in the following table addresses the flexibility of the technology's control system to operate in a stable way in different design scenarios (e.g. low / high inertia) and being optimized towards grid stability needs.

Table 9: Stability regarding FSM / LFSM

Stability regarding FSM / LFSM		
	Capability, boundary criteria and limiting factors	*measures to fulfil stability requirements*
HVDC	***medium*** - depends strongly on the characteristics of the other AC system (e.g. AC grid for interconnector or wind farm for offshore)	increase the capability of the other AC system, if possible
Statcoms	***none*** - Not applicable - there is no power source to provide (L)FSM)	Not applicable
PV	***high*** - can be provided by appropriate controls **Risk** - interactions with other dynamic requirements and Islanding detection tbc.	Redesign of control structure (depending on implementation of software and hardware)
Wind Type III / IV	***Medium*** - Can be provided by appropriate controls, but limited by capability to dynamically change active power (mechanical time constants of the rotor and drive train)	Redesign of control structure (depending on implementation of software and hardware)
BESS	***high*** - can be provided by appropriate controls **Risk** - interactions with other dynamic requirements and Islanding detection tbc.	Redesign of control structure (depending on implementation of software and hardware)
Synchronous Condensers	***none*** - Not applicable - there is no power source to provide (L)FSM	Not applicable
SPGM	***medium*** - Can be provided by appropriate controls, but limited by capability to dynamically change active power (mechanical time constants of the prime mover)	Redesign of control and actuator structure (depending on implementation of software and hardware)

Table 10: Amplitude Jump Power

Amplitude Jump Power		
	Capability, boundary criteria and limiting factors	*needed measures to utilize the capability*
HVDC	***medium*** **Range** - limited by thermal stress of semiconductors - depends on loading before the event - limited by mechanical load restrictions (Wind type IV) **Performance** - defined by control strategy; to be designed all-new - possible influence on design of lifetime	Higher inverter rating if the maximum current requirement is increased. Depending on resulting mission profile, larger DC-link may be needed
Statcoms		
PV		
Wind Type IV		
Wind Type III		
BESS		
Syncons	***high*** - limited by impedance	**none**
SPGM		

Table 11: Stability regarding voltage control loops

Stability regarding voltage control loop		
	Capability, boundary criteria and limiting factors	*needed measures to utilize the capability*
HVDC	***high*** **Range / Performance** - Depends on boundary conditions but can be provided by appropriate controls	Redesign of control
Statcoms		
PV		
Wind Type IV		
Wind Type III		
BESS		
Syncons		
SPGM		

Table 12: Overload capability boundaries

Overload capability boundaries		
	Capability, boundary criteria and limiting factors	*needed measures to utilize the capability*
HVDC	***low*** - Usually no overload capability by design - Depends on required profile (I(t))	All technologies: Overdimensioning of all main components (Semiconductors, DC-Link, AC-filter-components) Wind Type III & IV: Overdimensioning / Strengthening of mechanical components
Statcoms		
PV		
Wind Type IV		
Wind Type III		
BESS		
Syncons	***high***	none
SPGM		

8.3 Conclusion and way forward

There are various technologies which could provide capabilities for fulfilling the system needs outlined in chapter 6 of this report. Battery storage systems, HVDC and synchronous condensers and, of course, SPGMs already have a high technology readiness level with regard to the advanced capabilities outlined in chapter 6 of this report.

However, for converter based PPMs (wind, PV), there are fundamental restrictions with regard to the primary power generator when applying grid forming controls and most of these capabilities could be only be provided if the converter and plant level control structures for active and reactive power provision were fundamentally re-engineered towards a voltage and frequency control design.

In order to limit the risk of instability due to over or under voltage of the DC-Link interacting with the primary generator and at the same time contributing, within the design limits, as much as possible to phase jump and inertia power, the current limiting strategies would have to be fundamentally redesigned. At the same time, the amount of contribution (phase jump and inertia energy) is limited by the converter's inherent storage (meaning in most cases the "DC-Link") capacity. Increasing this capability would have a significant impact on the PPM's cost.

Due to technology specific dependence of the capabilities from the plant's actual active power operating condition, there will always be uncertainty of the available phase jump, inertia power and energy actually available in the system (converter-based technologies are usually not designed to provide overload capabilities).

The technology readiness of PPMs for such capabilities is currently very low, as the voltage-source-behind-impedance-behaviour contradicts today's design principles towards optimum energy yield, which is the basis of the plant's business model.

However, these technologies can be designed to be robust against phase angle changes and operation under low short circuit ratio (SCR) conditions and therefore minimize the need for phase jump and inertia power, without explicitly contributing to it by default.

In order to explore a set of future feasible default capabilities of PPMs, solutions for the challenges with regard to advanced capabilities should be investigated in order to increase their technology readiness level at least for those capabilities that, depending on the technology, are feasible to use in the long term.

For the time being, technologies with few inherent restrictions on active power reserve (such as battery electric storage systems and interconnector HVDCs with a secured primary instant active power source or synchronous condensers), can provide the required capabilities much more easily and help to fulfil the system needs in the near future. The technology readiness level of those technologies is much higher and could be utilized within a relatively short time frame, especially since it can be expected that some technologies (e.g. battery storage systems) will be installed in large volumes in the future for other reasons (e.g. driven by grid capacity constraints and electricity prices).

9 Compliance Verification and Monitoring

9.1 Background

The current version of the NC RfG differentiates between synchronous generation plant and non-synchronous generation plant. Non-synchronous generation plant is converter-based and grid-following. No specifications have yet been made for converter-based, grid forming generation plant. This also applies to the required proof of conformity and the associated simulations.

9.2 Basic Determinations

Specifications within the currently valid NC RfG regarding the required compliance monitoring (Title IV, Chapter 1, article 40-41) and the common provisions for compliance tests (Article 42) and compliance simulation (Article 43) are general and apply equally to synchronous and non-synchronous generation plant. There are no changes required for these basic specifications with regard to the differentiated consideration of grid-following or grid forming Power Park Modules (PPM).

9.3 Conformity tests for grid forming non-synchronous generation plants

Grid forming non-synchronous generation have, to a large extent, characteristics like those already encountered in the generation technologies considered or specified so far. These conformity tests include:

1) Participation in frequency regulation (FSM, LFSM-O/U): Those specifications are basically compatible with the technologies available to date. Accordingly, the verification procedures can be adopted in their basic structure. In this context, however, it must be pointed out that grid forming, non-synchronous generation units must have the ability to ensure stable power-frequency control without the aid of external inertia. For the operation of the LFSM-O/U, this means that the stability conditions resulting in the operating state when LFSM-O/U is activated, can be proven to be stable for a specified operating range in a sub-grid respective fictitious island network[3] situation. In this context, it must be verified that the electrical inertia is dimensioned according to the dynamic properties of the primary energy converter (PEC).
2) Voltage regulation and UVRT/OVRT behaviour: In the case of a continuous voltage control at the terminals of the generating unit and the possibly integrated FRT behaviour, or an explicitly designed FRT behaviour, the test procedures from the existing specifications can be adopted. This also applies if a superimposed plant controller is used.

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[3] Fictitious island network operation

A prerequisite for stable network operation outside the frequency range of market-based primary control (e.g. 49.8 Hz to 50.2 Hz) is the capability of network-connected PGMs to compensate for disturbances in active power balance within the LFSM frequency ranges and to subsequently maintain the network frequency at a stable operating point.

The active power control properties of PGMs required for this purpose shall be met for the fictitious operating situation in which the network beyond the connection point consists only of a constant PQ-load and, in case of grid following PGMs, an additionally provided inertia and short-circuit power. From a PGM perspective, this results in an operating situation in the network, which de facto corresponds to an island operation situation, but with the PGM remaining connected to the network connection point. This is not indicated during the transition from regular parallel network operation to island operation.

This situation is hereafter referred to by using the term “fictitious island network” or “fictitious island network operation”. Principally, it shall be distinguished from the defined “island operation” where the circuit breaker at the CP is open with the PGM detecting its open state. Therefore, explicit and specific island operation requirements such as those specified in ISO 8528 cannot apply to the “fictitious island network” or “fictitious island network operation”. Instead, the “fictitious island network operation” is a network operating situation where the network frequency is exclusively determined by the PGM itself. The stability criteria applied to the “fictitious island network operation” comes into force automatically when all PGMs contribute to LFSM-O/U.

3) The verification of grid disturbances (flicker, harmonics), existing in most national grid codes even though not in NC RfG itself, also do not require any verification beyond that required for non-synchronous, grid-following generating units.

For grid forming non-synchronous generation equipment, the following additional aspects are relevant. These must be included in the additional, specific conformity tests:

4) For PPMs, in addition to 1, it must be verified that the system behaves like a voltage source behind an impedance. The system reacts intrinsically to instantaneous to changes of the network voltage amplitude and phase angle, whereas the change of active and reactive current is only determined by the impedance, thus providing amplitude jump power and phase jump power.
5) The electrical inertia specified or agreed must be verified. Different procedures can be used for this. For example, it can be determined by load shedding or load disconnection, as in the case of the operation of a synchronous generator in an island network. If the properties are tested on a grid simulator, it is also possible to determine and evaluate the additional energy to be injected or withdrawn on the basis of the electrical inertia by measuring the power at the terminals of the generating unit in the event of an increase or decrease of frequency rise or a frequency drop in the simulated grid.
6) In addition to the verification of the electrical inertia itself, it must be proven that it is available in the agreed form for the agreed duration (energy). It must be noted, that electrical inertia that cannot be provided over the full frequency range places a burden on the overall stability of the system. In accordance with the specifications of the relevant network operator, proof of the reliability of the electrical inertia must therefore be ensured. In this context, it must be determined to what extent substitute solutions (e.g. chopper resistors) have been used.
7) Non-synchronous generation units have to provide damping characteristics according to specified requirements. Accordingly, it must be verified whether the specified requirements for damping behaviour are met. When defining and designing the test procedure, in particular it must be ensured that the specified damping characteristics are permanently present for the specified frequency range.
8) Furthermore, the behaviour of the non synchronous generation unit shall be verified with respect to the maintenance of the grid forming characteristics when the maximum current is reached. This includes active and reactive power prioritization (e.g. virtual impedance. as an implicit method).
9) A separate consideration will be necessary to verify the robustness of the power output with respect to voltage phase angle jumps, and whether in the case of defined phase jumps the demanded phase jump power is also permanently available (i.e. also in case of multiple faults).

9.4 Conformity simulation for grid forming non-synchronous generation plants

If, according to the respective requirements, property verifications are to be performed by simulation, the following basic requirements must be met:

1) It shall be demonstrated that the simulation model used is valid for the SCR found at the connection point. If this demonstration cannot be provided, the use of EMT rather than RMS models shall be required.
2) It shall be demonstrated by the submission of benchmarks (FRT cases, LFSM-O/U, virtual inertia, etc.) comparing the measurement of the plant and simulation of the mentioned cases with sufficient agreement, that the compliance simulations can be validly performed on the basis of the submitted simulation model.

3) In the event that special, stability-oriented verification situations are required, such as stability in island network operation, the simulation model shall be designed accordingly so that all required verifications have sufficient validity. It must also be ensured that properties that are particularly defined for grid operation (e.g. damping of active power oscillations) can be verified with sufficient accuracy and robustness by a properly defined equivalent grid at the grid connection point.

In addition to the compliance simulation procedures already specified for non-synchronous, grid-following generation plants, the following requirements for non-synchronous, grid forming generation plants in particular are to be proven by simulation:

1) Availability of the required electrical inertia and the specified energy content together with the involved controls to ensure the specified operating states (fault scenarios / benchmarks).
2) Verification of the required phase jump power with respect to a defined phase jump, including verification of robustness with respect to large phase jumps.
3) Verification of the behaviour of the generation unit when the current limitation is reached.
4) Behaviour in case of fault (FRT) with special focus on preservation of grid forming characteristics, maintaining synchronism with the grid and active/reactive current prioritization.
5) Verification of the required damping of power and frequency power oscillations in network operation over the correspondingly defined frequency ranges.

It can be assumed that the realization of grid forming characteristics is based on different concepts (e.g. VSM, specific grid forming droop control concepts). The requirements of manufacturers for confidential handling of models and data can be met by integrating original controller code in non-readable form (e.g. DLL) into the simulation model. An efficient solution is to be found on the basis of appropriate standardizations (e.g. FMI interface).

10 Roadmap for delivering capabilities

10.1 Background

The need for integration of grid forming technology into the electricity network is well understood as documented in the earlier part of this report. As to the mechanisms by which the technology is integrated into the system poses a number of interesting questions, not least, should requirements for grid forming be on a mandatory or market based principle, and if so, how would these arrangements work to ensure System Operator can manage the electricity network.

To answer this question, it is first worth noting some key issues which have been covered in the earlier parts of this report and which have a significant influence on the choice of options available.

All system operators are striving to operate safe, secure and economic systems, which are based on the principles of non-discrimination and transparency and the principle of optimisation between the highest overall efficiency and lowest cost for all involved parties. These principles apply irrespective of the generation mix and should facilitate both high and low levels of renewable generation.

10.2 Ancillary service / market based solution

The first element to address this issue is to understand that grid forming is not required from all plant at the same time. Unlike other grid code technical requirements such as fault ride through, which is required from plants 100% of the time to ensure maintenance of system frequency and voltage during disturbances, this may not be the case for grid forming. Based on studies run in Great Britain (GB) in 2012/2013 [10-1], it was demonstrated that in the GB system it was only when the volume of non-synchronous generation exceeded 65% that system stability issues were identified. Clearly this is important in addressing the wider question as to whether a mandatory or market based principle should be used. Knowing that grid forming is not required from all plants 100% of the time indicates that market based principles could be used in order to procure the service required at the lowest possible cost, though there is an choice as to whether to:

1) mandate the capability on all plant and use market mechanisms to select which plants to provide grid forming in the operational phase, similar to that used in GB for the purposes of securing frequency response; or
2) A commercial market framework to simply procure which plants provide grid forming when required.

From a system perspective it is a necessity to have a minimum volume of grid forming on a national basis for inertia purposes and on a regional basis for the provision of fault infeed / short circuit level. The system operator can then purchase the volumes required to satisfy system need in the most economical way.

As to whether a process is adopted mandating a grid forming capability, with market based principles used to procure which plants provide the service in real time as an ancillary service, or a pure commercial service with non-mandated requirements and a qualification process for those providers who contract to provide a service, are options which would both work. For the mandated solution, there is certainty in knowing all plant has the capability to provide a grid forming capability which provides a wide spectrum of providers but increases costs to developers, whilst also forcing some developers to fit a grid forming capability who may not wish to noting that some technologies are better able to provide a grid forming capability than others. On the other hand, a non-mandatory commercial approach provides an incentive for developers to provide the capability. This will be attractive to certain technologies where grid forming is relatively easy to implement but has the disadvantage that there are fewer providers to choose from and this could result in higher operational costs, especially where there is a requirement in a specific location.

The other approach that could be used which is being used in GB is to develop Stability Pathfinders [10-2] which effectively is a tender process requiring providers to commit to providing stability services at specific locations within the system for long durations of time. This then guarantees the provision of a service at a specific location using a range of technologies be it synchronous compensators, statcoms with a grid forming capability, smart loads or indeed generation with a grid forming capability. Whilst this again provides a degree of security and is extremely advantageous in the short term to provide the degree of stability required, in the longer term the use of generation or other providers to provide grid forming capability as an ancillary service may be a better solution as it is then more cost effective than building bespoke plant solely for the purposes of grid forming alone.

In this context it is important to note, as described in chapter 8, that the contribution to short circuit level, namely amplitude jump power can be provided by most converter-based generation technologies, as the inherent energy storage of the converter is considered sufficient to supply such functions. In contrast to this, inertia power requires an energy storage of a size that is not available in the current power park module design. Sufficient energy is intrinsically provided in the rotating body of synchronous coupled generating technologies and power storage modules, but for other technologies additional storage will be required to be installed at the site of the power generating module such as a battery or super capacitor. However, in case of fast controllable prime movers, some converter-based generation technologies may provide inertia power in over frequency, as a fast reduction of injected power is possible without energy storage. Likewise, they may provide inertia power if operated in curtailed mode with an excess on primary energy available. As a result, a differentiation between the amplitude jump power and phase jump power on one side and inertia power on the other side seams reasonable, as the technical effort for both differ significantly. Besides, the technical effort for inertia power may differ significantly over time depending on the availability of renewable primary energy and generating unit operating point.

10.3 Part of Grid Code - should it/ is it planned to be a mandatory requirement?

As to whether grid forming should be part of grid codes is an interesting question, but in general it is considered that it would better to have a minimum requirement in grid codes covering grid forming, rather than for it be absent from the codes. There are many examples of where there are non mandatory requirements in grid codes, for example black start, but to define the minimum requirements in grid codes has advantages in i) providing transparency and ii) grid codes themselves are subject to governance rules which provides better protection for developers.

A minimum grid forming capability requirement was implemented into the GB Grid Code in 2022 for these very reasons. The process used to implement the grid forming specification into the GB Grid Code was managed through Grid Code modification GC0137 [10-3].

Special attention must be paid to the fact that especially the mandatory requirement of inertia power would require additional energy storage in power generating modules, significantly exceeding the energy storage need for converter control and robustness. Mandatory inertia power requirement is therefore expected to increase the cost of PPMs and as a consequence increase the cost of the generated power significantly. This additional cost should be considered compared to the cost of other options for providing the identified system needs.

10.4 What sort of services are these mechanisms catering to? Emergency services or not?

Grid forming is principally required to ensure grid stability under network disturbances. Traditionally grid forming was an inherent feature of synchronous generation which naturally contributed to inertia and fault infeed both of which help to stabilise the grid during a credible fault. In a system dominated by converter based plant which do not naturally provide grid forming, credible system faults which would have been secured with synchronous plant can no longer be secured which requires minimum volumes of grid forming to be supplied on a national and regional basis. Hence grid forming is required to secure the system under normal operational conditions.

However, there is also an important role for grid forming under emergency and black start conditions. It has been usual practice to utilise SPGMs for black start purposes with grid following converters unable to provide such services, largely due to their inability to create their own voltage source. The advent of grid forming technology now enables converter based plant to provide a black start capability which is a very important vehicle for replacing the role traditionally provided by thermal SPGMs. The use of grid forming on a wind, wave, solar or battery installations can therefore be used for black start purposes.

As part of this work, it may be appropriate to mandate black start plants to have a grid forming capability which has been applied in GB.

10.5 Optimal solution of combination of grid support functions and grid forming capability

As noted above and since it is not operationally necessary to have a grid forming capability on all plant for all of the time, it would make sense to have a market-based solution which should aim to ensure the necessary volumes at minimum cost.

Based on this principle there are two options, these being i) to mandate the capability on all plant and then have a market arrangement to procure the right volumes in the right places or ii) to not mandate the requirement and have a market which provides the appropriate incentives to ensure the correct volumes in the correct locations.

Either option would work whilst noting that with option i) it pushes up developer cost but reduces price spikes during certain operational periods whilst in the case of option ii) it reduces developers costs but could result in price spikes under certain operational conditions if there are insufficient providers.

A possible option of how the arrangements could work are shown in Figure 2 below.

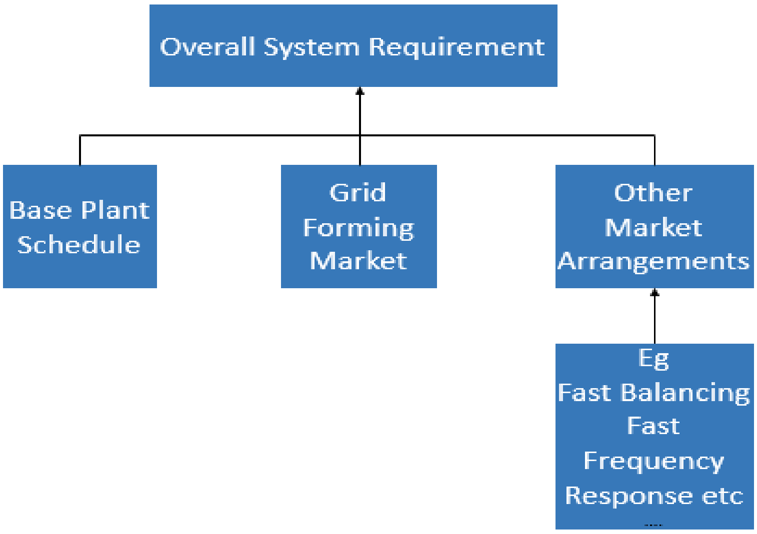

Figure 2 - Conceptual design of how grid forming could be implemented into the operational environment using market mechanisms

There are a number of options around a grid forming market which could take the form of a long term market where grid forming products are procured a long time ahead of real time, to take advantage of bespoke technologies, for example synchronous compensators, in addition to generation. This has the advantage of creating better price stability. Equally, a short term market could be used where the market is run for each half hour at the intraday stage. This has the advantage of utilizing generation assets which are generally designed for energy production but operational conditions such as high wind or solar conditions coupled with low system demand conditions enable grid forming to be provided at an economically attractive cost, though there may be periods where such volumes are limited. Either way, it is felt that a mix of long term and short term market arrangements are beneficial in optimising system costs.

In GB the system operator is currently working with partner organizations on the development of long and short term stability markets.

10.6 References

[10-1] H Urdal, A Dahresobh, R Ierna, C Ivanov, J Zhu, D Rostrom et al, System Strength Considerations in a converter Dominated Power System in12th Wind Integration Workshop London 2013.

[10-2] National Grid ESO Network Options Stability Pathfinder work https://www.nationalgrideso.com/future-energy/projects/pathfinders/stability

[10-3] National Grid ESO “GC0137: Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability (formerly Virtual Synchronous Machine/VSM Capability)”, https://www.nationalgrideso.com/industry-information/codes/grid-code-old/modifications/gc0137-minimum-specification-required, 2022.

11 Legal text proposal

11.1 Introduction to the text proposal below

This draft legal text proposal is based on the technical description of system needs and basic characteristics of grid forming power generating modules as described in chapter 6 and taking into account the input of all other chapters of this report. It is intended to help the ESC and ACER determine the legal text that should be proposed for the update of the NC RfG that ACER is engaged on in 2023.

There is a general agreement among the stakeholders regarding the technical need and implementation of grid forming characteristic in PPMs but there is no consensus reached regarding the application of this characteristic as mandatory, non-mandatory or optional capability for the different types A to D.

The expert group ACPPM considered it as most beneficial to define the technical aspects in a legal text proposal and highlight the different views regarding the application of this. In the following text square brackets [ ] are introduced to text that is not agreed by all stakeholders or is a view of one individual or a group of stakeholders. Behind each block in square bracket the group of stakeholders supporting this view is stated in curly brackets { }.

In some places notes have been added, which are not intended as parts of the legal text, but are intended as information for the entity using this proposal in view of NC RfG 2.0 to make sure the intention of EG ACPPM is understood correctly. In this context it should also be stated that EG ACPPM assumes that like all other articles in Title II the proposed text only applies to units that are actually active and generating power. However, we are at the moment not sure where this is stated, but it is obviously applied in this way.

This text has been developed and discussed by the experts involved over a period of three months needing significant effort by all experts involved. The experts of EG ACPPM see this text as the best possible compromise of the various views. EG ACPPM experts support this text and propose to theirs delegating stakeholders to support it. A formal approval within all the stakeholder organisations was not possible in the necessary timeframe to finalize this report.

At the end of this subclause, below the legal text proposal, each stakeholder is given the opportunity to present a short paragraph on why one specific squared brackets solution should be preferred.

11.2 Proposed legal text

Article Y

Requirements for type A power park modules

(to be included before Article 20)

6. [The relevant TSO in the coordination with the RSO shall have the right to specify that type A power park modules be capable of providing grid-forming capability at the connection point as defined by the following paragraphs.

If grid-forming capability was specified, then, after a transitional period of maximum 3 years after entering into force of this Regulation, type A power park modules shall be capable of providing grid-forming capability at the connection point as listed below. Member states shall have the right to shorten this transitional period based on system needs and urgency.]{proposal TSO perspective}

ACPPM Note for application of this proposal: The introduction of the term “transition period might” in this article not be legally sufficient to ensure that the requirement is only applied to plants being built after the transition period has elapsed. We ask that this is ensured in the final wording of the legal text.

[The relevant TSO with the agreement of the relevant DSO shall have the right to specify that type A power park modules be capable of providing grid-forming capability at its connection point as defined by the following paragraphs.

If grid-forming capability was specified, then, after a transitional period of 3 years after entering into force of this Regulation, type A power park modules shall be capable of providing grid-forming capability at the connection point as listed below. Member states shall have the right to extend or shorten this transitional period based on system needs and urgency.]{proposal DSO perspective}

[The relevant TSO with the agreement of the relevant DSO shall have the right to allow that type A power park modules be capable of providing grid-forming capability at its connection point as defined by the following paragraphs.]{proposal Manufacturer perspective}

[The Agency shall have the right to give a relevant TSO with the agreement of the relevant DSO the right to specify that type A power park modules be capable of providing grid-forming capability at its connection point as defined by the following paragraphs.]{proposal option 3}

(a) Within the power park module current and energy limits, the power park module shall be capable of behaving at the terminals of the individual unit(s) as a voltage source behind an internal impedance (Thevenin source), during normal operating conditions (non-disturbed grid conditions) and upon inception of a grid disturbance (including voltage, frequency and voltage phase angle disturbance). The Thevenin source is characterized by its internal voltage amplitude, voltage phase angle, frequency and internal impedance.

(b) Upon inception of a grid disturbance and while the power park module capabilities and current limits are not exceeded:

(i) the instantaneous AC voltage characteristics of the internal Thevenin source according to paragraph (a) shall be capable of not changing its amplitude and voltage phase angle while voltage phase angle steps or voltage magnitude steps are occurring at the connection point. The current exchanged between the power park module and the AC grid shall flow naturally according to the plant and converter impedances and the voltage difference between the internal Thevenin source and the voltage at the connection point.

(c) After inception of a disturbance (disturbances in voltage magnitude, frequency and voltage phase angle), the following shall apply within the power park modules capability including current limits and inherent energy storage capabilities of each individual unit. With inherent energy storage meaning an energy reserve available in physical components that are not built because of article Y requirements but may be used for the purpose of article Y, without effecting the design of the physical components of individual units.

(i) The internal voltage of each individual unit of the power park module shall be adapted according to a predefined dynamic performance in a stable and bumpless manner.

(ii) Where current limitation is necessary, the RSO may specify additional requirements regarding contribution of active and reactive power at the point of connection.

(iii) The power park module shall be capable of stable operation when reaching the power park module current limits, without interruption, in a continuous manner and returning to the behaviour described in paragraph (b) as soon as the limitations are no longer active. If reaching the current limit, the grid-forming behaviour must be maintained for responses as specified in (b) for disturbances that require the current to vary in the opposite direction of the current limitation.

(d) The RSO in coordination with the TSO shall specify the temporal parameters of the predefined dynamic performance in (c)(i) regarding voltage control.

(e) If according to Article 20, a synthetic inertia is specified, the dynamic performance according(c)(i) shall reflect this specified synthetic inertia.

ACPPM Note for application of this proposal: This proposal assumes that the term (34)"synthetic inertia" is defined as in RfG 1.0. (34) 'synthetic inertia' means 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; If this definition is changed or another term is used, this must be implemented here as well. ENTSO-E prefers not to use the term synthetic inertia but define a new term, but no term nor definition is provided.

[(f) For any grid-forming PPM, the PPM shall have the capability to activate or deactivate grid-forming mode as required by the RSO.]{proposal DSO perspective}

Article 20

Requirements for type B power park modules

ACPPM Note for application of this proposal: It is assumed that the square bracket solution of Article Y is inherited to article 20.

1. Type B power park modules shall fulfil the requirements laid down in Articles 13, except for Article 13(2)(b), and Article 14 and Article Y.

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NEW 4. If the requirements of Article Y (6). are applied,

(a) Article 20 (2)(b) and (c) shall not apply.

(b) type B PPMs shall fulfil the following additional requirements in relation to grid-forming capability. The TSO in coordination with the RSO shall specify the contribution to synthetic inertia. Where specified the power park module shall be capable of contributing to limiting the transient frequency deviation under high frequency conditions. [Additionally where specified, the storage module shall be capable of contributing to limiting the transient frequency deviation under low frequency conditions.]{TSO perspective}

Article 21

Requirements for type C power park modules

ACPPM Note for application of this proposal: The former Article 21 (2) (a) and (b) is considered obsolete once Article Y (6) and the following New Article 21 (5) are included in RfG. ACPPM assumes that Article 21 (2) of EU 2016/631 will be deleted in RfG 2.0

NEW 5. A type C PPM may be capable of providing grid-forming capability at its connection point as listed in Article Y (6) and Article 20 (4).

ACPPM Note for application of this proposal: It is assumed that the square bracket solution of Article Y is inherited to article 21 except for the TSO perspective where the proposed text is changed

[After a transitional period of maximum 3 years after entering into force of this Regulation, new type C PPM shall be capable of providing a grid-forming capability at its connection point as listed in Article Y (6) and Article 20 (4). Member states shall have the right to shorten this transitional period based on system needs and urgency.]{proposal TSO perspective}

If Article Y (6) is applied, type C PPMs shall fulfil the following additional requirements in relation to grid-forming capability within the PPM's capabilities as defined in Y (6) (c):

(a) The relevant system operator may specify that a study is required and may specify its scope in order to ensure that no adverse control interactions [or islanding events]{Proposal DSO perspective} occur during normal operating conditions (non-disturbed grid conditions), quasi immediately after a grid disturbance, during grid fault conditions and during the post fault operation where voltage and frequency profiles have returned to normal operating conditions.

(b) The TSO in coordination with the RSO shall specify the contribution to synthetic inertia. Where specified the power park module shall be capable of contributing to limiting the transient frequency deviation under low frequency conditions.

(c) For the provision of additional energy above the inherent energy storage the TSO shall apply to the NRA for the right to require the provision of additional energy beyond the inherent energy storage in coordination with the RSO.

Article 22

Requirements for type D power park modules

Type D power park modules shall fulfil the requirements listed in Articles 13, except for Article 13(2)(b), (6) and (7), Article 14, except for Article 14(2), Article 15, except for Article 15(3), Article 16, Article 20 except for Article 20(2)(a) and Article 21.

11.3 Stakeholder view on squared brackets and proposed legal text

In the subchapters below all stakeholders were invited to contribute an explanation why the various views are specifically relevant. Also stakeholders have the options to add comments to the agreed common text or recommendations for further work.

11.3.1 CENELEC

CENELEC is a Standardisation organisation where all stakeholders also present in ACPPM contribute as well taking into account the respect of technical neutrality. As a result, there are members in CENELEC that will support any of the proposals. However, we want to emphasise two aspects:

- Relative to the TSO-perspective we consider it important that an agreement is reached with the relevant system operator regarding the integrations of grid forming PPM into its grid. We fear that the proposed “coordination” may lead to national implementations that are not technically feasible for a DSO e.g. if the schedule is not sufficient to adapt protection schemes or the cost to reconfigure the network is too high and not acceptable sufficiently solved in within the regulatory framework of a member state.
- Furthermore, CENELEC must emphasise that the proposed provided text is not able to provide the needed degree of technical details to allow a correct harmonization in Europe. The text poses the risk, that national implementations deviate significantly hindering the common market of goods and requiring manufacturers to develop and certify many different control characteristics while a single development could provide for all system needs The approach of national implementation in RfG 2016 resulted in many national solutions and was therefore undermining harmonization and a common market and rendering it difficult to any RSO to perform the correct simulations necessary to take consequent decisions. To avoid a further differentiation of national requirements especially for technically challenging items such as grid forming, the application of international and European standards must become the principle in all member States and national implementations deviating from or exceeding European Standards must become the exception. Therefore, the reference to standardisation in Article 7 needs to be strengthened and standards must not only be “considered” but must be “applied” and deviations from European Standards must be reasoned and should only be accepted by NRAs if technically not avoidable.

11.3.2 COGEN EUROPE

COGEN Europe sees two critical issues for micro-cogeneration with the above proposal for the legal text:

1) Formally, asynchronous generators are classified as PPM (‘power park module’ or ‘PPM’ means a unit or ensemble of units generating electricity, which is either non-synchronously connected to the network or connected through power electronics, and that also has a single connection point to a transmission system, distribution system including closed distribution system or HVDC system; NC RfG, Art. 2(17)).

   Thus, it is important to explain that during the development of the second edition of NC RfG some kind of differentiation between inverter based PPMs (e.g. solar, wind etc.) and ASG type of PPMs is needed. Any additional requirements on PPMs with asynchronous generators up to 50 kW (see Energy Efficiency Directive, EED, 2012/27/EU, Article 2(39)) should be taken for granted and exempted from conformity testing, as the asynchronous generator is the working horse in the niche market of micro-cogeneration. This would also apply for asynchronous generators used in micro-hydropower, micro-windturbines and other micro-generators.

2) The second issue relates to power electronics, which are used in the micro-CHP industry either as DC/AC converters for fuel cells or as AC/AC "electronic gears". Even if only the software needs to be updated, which is not expected, the inverter will be a new product which requires development resources as well as certification costs. Considering the fact that micro-cogeneration is still a niche market and not selling hundreds of thousand units per year, the costs for this update are specifically high and the class of micro-cogeneration units is still not systematically relevant. Probably, power electronics manufacturers will focus their development resources on their A-lines and niche products might be neglected.

   The already implemented derogation process in the NC RfG is not a solution, as first there is a risk that it will not be granted and second the transaction costs are high because an application has to be made in each EU member state for a product line that is not sold in large quantities such as PV inverters but can be considered as part of a tiny market segment. Therefore, an exemption for micro-cogeneration is needed up to 50 kW (according to the EED) which optimises dovetailing between different legal areas. The principle of proportionality and the optimisation between the highest overall efficiency and lowest total cost for all involved parties (see NC RfG – Commission Regulation (EU) 2016/631, Whereas #15 and Article 7) should be applied to protect niche market products.

11.3.3 ENTSO-E

Regarding the text square brackets [ ] that appear in the legal text proposal, ENTSOE would like to provide the following comments in order to explain its view on and the reason why some proposals from specific stakeholders should not be accepted by ACER:

1) ENTSO-E supports the position to have grid forming capability as **mandatory requirement** for type B to type D power park modules (**within the power, voltage, current and energy ratings of the PPM**) after the transitional period of maximum three years. This decision for type B and where applicable type C should be made in coordination with the DSOs.
2) ENTSOE considers that it is important to include a transitional period for the implementation of the requirement as mandatory as this will provide a preparation period for the development of the grid forming technology and harmonized values across EU specifications/requirements.
3) ENTSOE does not support the activation or deactivation of grid forming mode as it could be dangerous for system operation. Therefore, we consider that this provision should not be included.
4) ENTSOE considers that for electricity storage modules (ESM) the capability to respond to transient frequency deviation under low frequency disturbances for type B and above should be mandatory (**within the power, voltage, current and energy ratings of the ESM**). The latter does not apply for the other technologies that depend on the primary energy source.
5) ENTSOE considers that the term synthetic inertia should not be used when talking about grid forming technologies as ENTSOE considers that it could be misinterpreted by other stakeholders. In some countries this term is used and implies a time response delay. ENTSO-E proposes to use the sentence “limiting the transient frequency deviation” instead of synthetic inertia.

11.3.4 EU DSO Entity

DSOs understand the TSOs’ need to accommodate the growth of renewables, and the retirement of traditional large synchronous generation. However, DSOs’ belief is that a high penetration of grid forming converters will make unintentional islands much more likely, and islands are generally forbidden on safety and legal grounds. The state of the art for managing islands on distribution systems involves significant investment in network assets and control equipment. To accommodate the risk of islands across all the locations where grid forming converters might be installed in future would, based on DSOs' knowledge of the state of the art, require a very significant investment programme in network and control equipment, potentially affecting every MV/LV substation.

The DSOs' know that DSO networks with significant volumes of grid forming converters have not been sufficiently studied so that the effects and risks are sufficiently understood to propose sensible mitigations. In addition to the islanding risk, it is not clear that there will not be other issues, such as instability, caused by a high penetration of interacting grid forming generation. Currently DSOs do not believe that there is sufficient standardization of grid forming technologies to allow comprehensive modelling of these issues, and believe that experience with pilot installations and demonstrators on DSO networks will be important.

DSOs are also not sure that all possible options available to TSOs have been sufficiently evaluated, particularly when the costs and efficacy of those options needs to be weighed against the likely costs of accommodation of grid forming converters on DSOs' networks.

Hence the DSOs' view is that a blanket deadline for all new generation to be grid forming is premature, and certainly 3 years after entering into force is likely to be far too short if any scale of DSO accommodation programme is necessary. The DSOs believe that flexibility must be retained in the legal drafting such that the requirements are only "turned on" when the mitigations are understood and the timeline for sufficient implementation known.

To cater for the situation where a grid forming converter is connected to a DSO network and where the DSO assesses that the risks and consequences of islanding are inappropriate, the RSO shall have the capability to require that converter to be grid following.

11.3.5 SolarPower Europe

SolarPower Europe supports to add a general specification of grid forming capabilities in the NC RfG 2.0 as a first step for further technical standardization. However, we recommend to introduce grid forming capabilities by commercial incentives, object to make grid forming capabilities an optional or mandatory requirement in the connection codes for generators and propose to introduce the concept of "giving the TSO/RSO the right to *allow* grid forming" for the following reasons:

- *The requirement approach "within the capabilities" creates uncertainties*:
  To mandatorily stipulate a function which is to be provided "within inherent capabilities" makes it nearly impossible to find neutral acceptance criteria for fulfilling the requirement. There are a lot of potential complex influence factors in hard- and software of PPMs (such as PV-plants) and their control capabilities. Who else than the manufacturer can judge what the "inherent capability" of a unit is? It is very likely that the requirement is not very robust and creates a lot of uncertainties among the stakeholders.
- *Ancillary service market based sourcing is much more efficient and non-discriminatory:*
  Sourcing grid forming capabilities from technology open designed ancillary service markets with distinct technical specifications and unambiguous acceptance criteria directs development capacities to most efficient sources to fulfil future system needs
- *Grid forming technology readiness level is extremely low for PV systems:*
  For PV there is no experience on applying grid forming controls, just theoretical concepts with low potential contribution and risks with regard to stable plant and grid operation.

- *A Grid forming requirement for Type A PPMs conflicts with DSO's requirements:*
  Making grid forming an optional requirement for type A PPM produces a conflict with the DSO's requirements on disconnecting in unintended islanding situations. It may lead to double development and validation effort, since the same unit may (1) have to or (2) mustn't run in "grid forming" mode, while in both modes having to fulfil NC RfG's further requirements. Implemented grid forming capabilities may never be used in practice due to objections of DSOs. Not knowing the methodology for type power thresholds in NC RfG 2.0 increases the risk of high development efforts for manufacturers without significant benefit for grid stability.
- *There is an alternative:*
  Large scale grid forming battery storage systems (and other technologies) are available in the market and could provide such capabilities within an ancillary services framework. Battery systems are expected to be utilized widely in combination with or in close proximity to PV power park modules in order to provide flexibility in power generation under grid capacity constraints and to support day/night power balancing. Those battery storage systems can provide grid forming capabilities with a much higher availability and in a symmetrical way e.g. at the connection point of a hybrid plant (rather than at every PV generating unit), due to the ability to increase power output from normal operating points.

SolarPower Europe's proposal is therefore to **allow** to apply grid forming capabilities as soon as they are maturely defined based on the provided framework of this legal text proposal, but to **not allow to request** the capabilities within the inherent capabilities from **all** power park modules.

Instead, reliable and clearly quantified grid forming capabilities with secured availability should be sourced using stability market approaches, while PPMs may fulfil quantifiable robustness criteria in terms of riding through grid disturbances and of synchronization, giving maximum certainty for both manufacturers and system operators.

11.3.6 Wind Europe

- The lack of clear details of grid forming requirements in the proposal <u>may</u> result in unnecessarily different national implementation requirements thereby undermining European harmonization.
- Grid forming can be provided in various ways. Fast control functions will depend on hard-wired equipment in inverters, which are usually located in the nacelle. This means that wind turbine owner will have to decide during procurement if the turbine shall be grid forming or grid-following. This makes the process costly. Solutions with basic/limited performance can also be provided via software changes, but will be limited by the turbine's current, power, energy & mechanical limits. Limits can be overcome but more capability can be provided by hardware changes, especially storage or a bigger chopper, representing significant costs. Hence, in NC RfG 2.0 mandatory requirements should be limited to current, power, energy, and mechanical capability of today's turbines. Mandatory requirements should only describe software-based capabilities. This applies to all types A, B, C & D PPMs.
- To fulfil the requirements for synthetic inertia a wind farm will either have to a) install energy storage, b) curtail output, or c) deliver a limited amount of synthetic inertia based on the inherent rotational energy from wind turbines. This cost will be reflected in the prices of wind turbines. Moreover, such a turbine modification will need significant time for development, testing and certification. Software only changes can provide a limited

inertial response in the existing fleets. Requirements which imply hardware changes like battery storage, or require curtailment, need to be incentivized rather than being mandatorily required. This will allow a market-based approach[4], so that the cheapest provider for this specific grid service is chosen. We propose that the wording on synthetic inertia in the NC RfG should follow the black start requirements (ENTSO-E NC RfG Article 15, Paragraph 5 ff) for requirements going beyond today's design and those that increase costs.

- Our proposal for Article 21, 5, (b) & (c) of this document: Current text to be replaced by –
    - (b) The TSO in coordination with the RSO shall specify the contribution to synthetic inertia. Where specified the power park module shall be capable of contributing to limiting the transient frequency deviation under low frequency conditions within the power park modules inherent energy storage and mechanical limits, where applicable.
    - (c) Contribution to synthetic inertia under low frequency conditions is not mandatory without prejudice to the Member State's rights to introduce obligatory rules in order to ensure system security.
    - (d) Power-park module facility owners shall, at the request of the relevant TSO, provide a quotation for providing inertia capability above the inherent energy storage. The relevant TSO may make such a request if it considers system security to be at risk due to a lack of inertia capability in its control area.
- The decision of whether to have grid forming capability defined at a plant or a unit level needs further discussion.
- Proposal for Article Y 6(d): "The RSO in coordination with the TSO shall specify the temporal boundary parameters of the predefined dynamic performance in such that boundaries of dynamic performance lead to reasonable dynamic performance over a range of grid conditions and events over the lifetime of the application. Assumptions on the grid representation during assessment of dynamic performance shall be provided by the TSO."
- We expect that prior to any implementation the proposed changes will undergo a CBA and that the results are consulted upon with all stakeholders.

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[4] WindEurope position paper on grid forming capabilities, March 2023

12 Recommendation for future work

12.1 Further Research

From the analysis in chapters 6, 7, 8, 9, 11 it is clear that the impact of grid forming converters is not fully understood. This is in relation to global issues of stability and performance, as well as uncertainty to their effects in distribution networks, which have significantly different characteristics to transmission networks, where the bulk of the current research has been focused. For some technologies (especially wind and PV) research and development are needed in order to utilize their theoretical capabilities and to mitigate the risks from the implementation of a fundamentally new control structure.

Accordingly the EG recommends that

- more research is undertaken on the effects of high penetration of grid forming converters in DSO networks taking into account different operation rules and criteria;
- Research is also needed that focuses on stability issues as grid forming converters are deployed in all (TSO and DSO) networks and how to deal with technology specific grid forming capability limitations;
- Further analysis is undertaken of the operational aspects and needs of the SOGL and NC E&R.

12.2 Standardization

Chapters 7, 9 and 11 highlight that there is as yet no standards for grid forming requirements and behaviours. Hence at present it is not possible to forecast the exact behaviour of grid forming converter plant even though it might be stated to be in compliance with high level grid forming converter requirements. Requirements should be standardized for all of Europe. In addition chapter 9 points out that:

- New conformity tests are required for:
    - Essential robustness (i.e. source behind impedance)
    - Inertia
    - Damping and stability
    - Current limits
- New models for digital simulations that represent:
    - Inertia
    - Phase jump power
    - Behaviour at current limits
    - FRT, and especially the preservation of grid forming behaviour
    - Damping of oscillations
    - Interactions and hierarchies of the above
- Validation of the above characteristics of simulations

Ideally the development of these tests and properly detailed models to allow DSOs to perform simulations would also be standardized, and may even identify further research that needs to be added to the existing list in 12.1 above.

12.3 Implementation

There are fundamental choices to be made as to how far the introduction of grid forming converters should be mandated, versus what might be brought forward by commercial incentives. There are also choices to be made as to what sizes and/or types of plant to apply mandatory requirements to, since between the technologies there are large differences in terms of grid forming technology readiness level and their potential capability to contribute to the fulfilment of system needs.

Chapters 6 and 11 suggest that it is premature to mandate grid forming converter for PPMs introduced into Europe in the near term. However chapters 6, 7 and 8 suggest that grid forming converters with high technology readiness can be introduced onto HV networks in the short term, but more research and development before introducing them in any numbers on to MV and LV networks.

Notwithstanding the further research and development needed, the high level requirements relating to robustness, undervoltage behaviour and RoCoF capabilities and the proposed legal text in chapter 11 should be included in the pending update to the NC RfG.

Annex A

A.1 Technologies (applications, characteristics and technical readiness related to system needs and advanced capabilities)

A.1.1 Synchronous Power Generating Modules (SPGMs)

A.1.1.1 Hardware and Primary Source Characteristics

SPGMs encompass a very wide range of technologies from very big hydro units and nuclear power plant to big combined cycle power plant based on gas and steam turbine, industrial cogeneration plant including gas turbine and reciprocating engine, to very small units like mini hydro units, microturbines etc.. SPGMs are characterized by intrinsic inertia and natural contribution to FRT capability. They are considered to naturally contribute to the stability of the system.

The dynamic characteristics and capabilities of the different technology may depend on the primary source of energy (e.g., water, fuels, etc.), but also on associated process of which the unit is part for example the heat process in a cogeneration plant.

Except for some very small units (Type A; few kW) which have limited to no active power capabilities, in general SPGMs are able to provide active power control as function of the frequency. Some technology can have some limitation associated with very fast ramp especially when increase of power is requested.

Phase jump power could be possible for limited angles and depending on technology.

Voltage control and reactive power capability are associated to the design of the generator, including the excitation system, and of the voltage controller.

A.1.1.2 Control Capabilities and structure

The SPGMs can be synthetically defined as composed by a prime mover, its correspondent control system, a synchronous generator and its control system.

The prime mover is the system converting the primary source of energy in the form of mechanical power transferred to the synchronous generator by a rotating shaft.

Active Power control of a synchronous machine is regulated by a governor, and for voltage control there is an excitation system. The active power control can be realized via different control structures. With regard to the capability for stable FSM/LFSM in closed loop operation and voltage control, the design of the control structure may have to be redesigned for future power system needs with a high share of PPMs and low overall inertia and potentially large RoCoF-values.

A.1.2 Power Park Modules (PPMs):

A.1.2.1 Wind Power Generating facilities

There are different types of wind turbine generators (WTG) which have to be distinguished. IEC 61400-1 provides a classification. Type III WTGs are connected to the grid via a doubly-fed induction generator (DFIG), Type IV WTGs are coupled via a full converter.

Contribution to frequency control can be provided by both Type III and Type IV WTGs as commonly required by the national grid codes. Negative frequency control (i.e. power decrease with increasing frequency) is common, positive frequency control (i.e. power increase with as frequency drops) is possible in principle, but would require output to be curtailed prior to the frequency drop, before which is not economical. It is not widespread yet [A-1].

Exact “inertia response” in its traditional physical meaning is not possible with grid following inverter control, as the turbine rotor and electrical power system are decoupled in current WTGs. They are designed to maximize energy yield at minimum cost. To that aim, it is better to not have a rigid coupling. However, something similar to inertia is available from today’s wind-OEM, type 3 as well as type 4. Called typically “inertia emulation” or “synthetic inertia”. This is very different to grid forming and has been available as a feature for more than ten years. In contrast to the traditional concept of physical inertia, this is a control-based, relatively quick (within 100ms - 500 ms) active power response to underfrequency situations in the grid. It is using the inertia of the rotor, by intentionally changing its operating point, deviating from the steady-state operating point of maximum power tracking. It can respond to grid-frequency disturbances within significantly less than 1 second, but still responds more slowly than the traditional and fully physical inertia provided intrinsically by a synchronous generator. This additional active power can be maintained only for some seconds, otherwise the rotor would slow down too much. Hence something similar to “inertial response” is possible but depending on the point of operation. After the additional power has been released there is a significant drop in power output (“recovery phase”) which may have issues for stable power system operation. It should be noted that the term “Synthetic Inertia” is defined in RfG as “means 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”. That said and as noted above, in the past the term “Synthetic Inertia” and “Inertia Emulation” have been used to define commercial products. The electrical performance of these commercial products is quite different to the definition of “synthetic inertia” as defined later in EU 2016/631 (RfG).

In case of negative phase jump power / negative inertia power it may be theoretically possible to use a passive chopper as it is used today in some products to dissipate active power during grid faults. However, it would significantly affect the design requirements and the chopper’s capacity if it was expected to provide multiple functions. Otherwise this would restrict its capacity in each function.

The key difference between grid forming and grid following control modes of both Type III and IV wind generation is the inverter control within the first quarter to full period of the cycle following a grid fault. The fast (0 - 20 ms) response to the change of the phase angle for either continuous angle increases (“inertia”) or phase angle jumps (“phase jump power”) requires active power.

Fast voltage control (voltage amplitude response) requires active power only and could be provided by both Type III and Type IV wind turbines, depending on control and the rating of the inverter.

A.1.2.2 Wind Power Generating facilities Type III (“DFIG”)

Hardware and Primary Source Characteristics

The controls and stability of Type-III wind turbines operating in grid forming is different to Type IV wind turbines with full converters and to SGs. Grid forming control always tries to implement the behaviour of a voltage source behind an impedance. In a DFIG (with a wound rotor induction generator) the stator is directly connected to the grid and is operating at grid frequency. The power from the rotor windings (operating at variable frequency depending on the rotor speed) is provided through the WTG converter to the grid – the Type III WTGs therefore also have a converter directly connected to the grid, but it is rated at typically 25% to 33% of the WTG active power.

This design approach allows variable-speed operation of the wind turbine, while requiring a smaller converter compared to full converter Type-IV wind turbines. The Type-III WTG converter exchanges only the generator slip power that is fraction of the nominal power of the wind turbine.

Control Capabilities

The DFIG WTG in the grid forming and grid following mode controls voltage angle, amplitude and frequency of the rotor voltages. Since the stator is directly connected to the grid, Type III WTG inherently tend to respond to voltage changes in the grid like a synchronous generator, i.e. in a grid forming mode. But the large inductance of the generator leads to higher currents compared to Type IV WTs, especially under unbalanced conditions, which requires higher overrating of the converter compared to Type IV inverters.

Comparable to synchronous generators, deep voltage dips can lead to a DC-component in the rotor flux. In synchronous generators, decaying fault currents are normal. Grid codes often focus on Type IV WTG and require tightly controlled currents during grid faults. In Type III WTGs the decaying currents from the flux of the DC-component can only be controlled indirectly (e.g. limited via the grid side converter). The currents during the fault are much better controlled than of a SG, but not as precise as from a Type IV WTG.

The response time to control requests of a Type IV WT is comparable to full converters, with time constants smaller than 15ms. If Type III WTs are equipped with a large DC-link chopper, they may be able to absorb the entire energy of the WT during a fault. In this case, the turbine mechanical structure is not exposed to the fault. Type III WTs and Type IV with a small DC-link chopper only respond to voltage dips with an increase in rotor speed and drive train oscillations, this may lead to higher stress on the drive train. This is a manufacturer specific design question – to invest in a larger chopper or in a possibly slightly stronger drive train.

A.1.2.3 Wind Power Generating facilities Type IV (“Full Converter”)

Hardware and Primary Source Characteristics

In Type IV wind turbines, the generator is only connected to the grid via a “full scale” converter. The power converter is the intermediary between the generator and the grid. Generator types like squirrel-cage induction (SCIG) generators and wound rotor synchronous generators (WRSG) can also be used here, but the permanent magnet synchronous generator (PMSG) is most popularly used. The turbine can be with (PMSG, WRSG, SCIG) or without (high pole PMSG or WRSG) gearbox.

Inverters are built physically as a voltage source (DC-link with IGBTs (insulated gate bipolar transistors) behind an impedance. The response of such a system depends on how the inverter controls the IGBT-switching. Without very fast (<1ms) control of the inverter currents or corresponding internal voltage (depending on the OEM’s implementation), step changes of the grid voltage, step changes in grid frequency and voltage would quickly lead to currents beyond the design limits of the inverter. Grid following control allows a tight control of the currents (by modifying the inverter’s internal IGBT modulated voltage), allowing a precise control of the generator torque without exceeding the design limits of the converters.

Inertia, meant as active power response to a step change (or fast change) of phase angle between two voltage vectors connected via an impedance requires active power. The energy of the DC link of a Type IV converter is far too small for enabling “full” grid forming operation. But as described above, in contrast to PV systems, WTs have kinetic energy stored in the rotor (hub and blades). The energy stored there is much larger than the energy needed for one cycle of grid forming operation following a grid fault. Besides control and inverter rating, the capability to provide phase angle power and inertia also depends on the capability to provide sufficient energy quickly to the DC-link, either from the rotor/generator, and/or from a separate battery storage system. For a seamless contribution of grid-stabilizing active power to the grid (different to the pre-event max. power point operation), a very different control approach and/or e.g. a significant increase of DC-link capacity would be needed, compared to today’s Type IV technology.

Requiring inertia for more than one cycle, is a new requirement for wind turbines. Depending on the time and energy required and the operating point of the turbine, an additional energy buffer (or storage) may be required. But this is not specific for grid forming, it can be provided by grid following control as well. A difference between grid forming and grid following exists only in the first 0 - 20 ms after a grid event.

Control Capabilities

In Type IV WTGs, the converter controls vary, depending on the prevailing wind conditions. The voltage at its terminals is a consequence of (active and reactive) power flow and grid impedance. This voltage is “observed” and extreme values lead to tripping, but it is not necessarily controlled in an active way at a WTG level. If voltage control is required by a grid code, this usually applies at the WF point of common coupling (PCC) and therefore is managed by the WF controller. This measures relevant quantities at the PCC and can send commands for Q and/or P to the individual WT. The exact implementation of controls (LFSM-O, LFSM-U, FSM, Q(U) etc. depends very much on the specific OEM.

During grid faults the focus in recent years, and in related grid code requirements, has been for fast fault current contribution, for both symmetrical and asymmetrical grid faults. Such faults affecting the grid voltage magnitude mainly address the reactive current provision by the WT. An additional requirement may be to maintain the active current contribution during FRT at a certain level (GB and IE, typical for smaller / isolated power systems). Strict current limits in the inverters lead to non-linear response during disturbances.

Fully sized inverters in Type 4 WT allow for a quite free parameterization of this fast fault current contribution. Rise times of less than 30ms after the start of the voltage drop are industry standard, due to specific grid code requirements [e.g., German VDE-AR-N 4110].

With regard to active power control, the focus is on maximizing the energy yield, as this is what the owners are paid for. LFSM-O is technically relatively easy and standard. Reducing power is done by pitching blades out. This takes a few seconds and is in line with current applicable grid code requirements. Faster response times are under discussion (ACPPM, VDE-FNN] and might be achievable by using e.g., chopper resistors. However, while such changes are not formal requirements, nor incentivized, the OEMs will not invest is such capabilities.

In contrast, LFSM-U is not possible under normal operation conditions. “Normal operation” for a WT means maximum power point tracking, always harvesting the maximum available active power based on the actual wind speed. There is no power headroom upwards at any time. Only if a WTG is curtailed to operate below the maximum available active power, can a positive active power contribution for LFSM-U, or FSM, be provided. Such operation being permanent would have a commercially prohibitive loss of energy yield.

A.1.2.4 Photovoltaic (PV) Power Generating facilities

Hardware and Primary Source Characteristics

Power park modules based on photovoltaic energy use power electronic inverters in order to convert the DC power provided by the PV modules into AC power. The PV module characteristics and the irradiation lead to a nonlinear, time-variant I/V characteristic curve of the PV generator. The inverter determines the optimal operating point in order to control the DC power taken from the PV generator and convert it to AC. In normal operation, the goal is to operate the PV generator at the maximum power point (MPP). The rated DC power of the PV-array is typically larger than an inverter’s rated AC output power, enabling to reduce the specific costs for energy generation.

Small inverters for residential applications up to about 4-5kW are single phase inverters. Above that value, usually three-phase inverters are applied and used in all power classes up to several hundreds of MW.

State of the art inverters for PV applications consist of single or multi-stage voltage source inverter power electronic topologies (see also [A-1]) applying pulse width modulation. This means, that physically in case of a voltage phase jump at the AC-side, the current flowing from the DC to the AC-side can change instantly and therefore charges or discharges the DC-link (and thus behaves like a voltage source behind an impedance). However, in order to minimize the DC-link capacity which takes a significant portion of cost and volume of a converter and in order to protect the semiconductor devices from overload, this current is usually limited very quickly by the current control loop.

Since overload capability does not provide additional value for PV-applications, the maximum AC output current is typically optimized towards 1 p.u. Thus, the usable operating range in terms of active power is between zero and the actual power potential of the primary PV-generator, depending on the irradiation. The short-term maximum power and supplied current largely depends strongly on the thermal limits of the semiconductor devices and maximum current capability of other components (filter inductance etc.).

The DC-link is usually designed with respect to electromagnetic-interference performance, lifetime, quasi-stationary voltage ripple limitation and considering the transient power flow due to small inverter control synchronization delays e.g. during fault conditions of the power grid. The absolute size of the DC-link capacitance depends on the power electronics topology and is typically optimized to a minimum. Depending on the operating conditions, the energy storage capacity of PV inverter systems can provide power for only a few milliseconds with a negligible quantity of energy. If the DC-link voltage drops below a critical value, no active power can be fed into the grid.

Control Capabilities

Within the operating range, for today’s PV inverters the achievable control dynamics (response to setpoint changes, e.g. according to the LFSM function) is relatively high (a few tens of ms), since there is no physical inertia inhibiting the actuating inverter voltage vector shift. At a plant level the dynamics depends strongly on the communication infrastructure within the plant.

With regard to “*stability and dynamics of the LFSM function”*, the control loop usually includes a measurement of the grid frequency. The bandwidth of the measurement is limited in order to achieve robust values including those under disturbed voltage conditions. If implemented on plant level, again communication delays impact the control dynamics.

Providing constant active power headroom with high accuracy, e.g. in order to be able to provide a guaranteed power reserve is (besides not usually being economically usually) ambitious, especially during (the usually regular occurring) changes in irradiation. However, if operated in a curtailed mode to a fixed output power (e.g. utilizing the plant level control), the reserve may be utilized during emergency situations.

Despite the reactive power control functions for voltage support, the direct AC voltage control with *“amplitude jump power”* is not a capability of photovoltaic inverters today. Regarding this, a specific requirement and subsequent development has to be considered even for large scale PV power park modules, since today’s control schemes have to be adapted significantly. However, such capability is possible, but has to be investigated with regard to effects on hardware design.

As mentioned above, due to very limited electrical storage needed for controlling PV generators effectively, the current control and protection with regard to a disturbed response is usually very fast (µs to ms), in order to keep the power balance between the input and the output of the inverter. In case of a grid voltage phase angle change, the current is usually controlled within one and a few cycles to keep the power at its current setpoint.

Today, the resynchronization capability and a certain level of robustness against voltage phase angle steps is available and may be further improved, but there is not necessarily a significant phase jump power comparable to grid forming controls.

Providing significant volumes of explicit *phase jump power or inertia* in either direction (increase and decrease of active power) under disturbed conditions which is comparable to that of a grid forming converter with (in relation to the transient need) unlimited energy is not state of the art for photovoltaic systems, even for negative phase jump power. Such capability may be theoretically possible, but requires fundamental changes in control structures, with risks regarding the overall dynamic behaviour and the interaction with requirements for other transient conditions, such as fault ride through etc. Especially ensuring synchronization in case of negative phase jumps becomes a challenge if grid forming capability shall be applied to PV systems.

From today’s viewpoint, changing the control structure towards providing a defined phase jump power risks losing the stability of the power balance in combination with the PV generator’s strongly non-linear I/V curve and a voltage collapse of the DC link.

It is very probable that the energy needed for a significant contribution to phase jump power in positive and negative direction would – for stability reasons – therefore have to result in a significant increase of DC-link capacity by at least the factor of 10 as a first approximation, while this may depend on the converter’s power electronic topology and number of conversion stages.

With regard to negative inertia in combination with negative phase jump power, these challenges become larger, since the active power balance between the (nonlinear) DC and AC side would have to be matched during such large excursions very exactly. It can be expected, that such a capability would also have to result in a necessary significant increase of DC link-capacity.

PV systems in the distribution network (especially LV) usually have to fulfil requirements to detect unintended islanding situations and trip under such conditions. Such opposing requirements for PPMs connected to the distribution network (robust and stabilizing control to support the overall system vs. protection requirements regarding the distribution network) have to be clearly identified and prioritized in order to obtain a predictable behaviour.

A.1.3 Non-Power Generating Module Applications

Besides power generating modules, further applications and technologies such as fully integrated network components or energy storage facilities may be utilized to provide additional capabilities for grids with high penetration of PPMs. The most important applications identified are the following:

A.1.3.1 Static Synchronous Compensators (STATCOMs)

Hardware and Primary Source Characteristics

STATCOMs must be distinguished between classical STATCOMs and STATCOMs with extended storage and Energy provision (“E-Statcom”) [A-2]. Both are typically constructed with modular multilevel converters operating at several tens of kilovolts. The modular multi-level converter (MMC) provides a minimum of electrical storage in its submodule capacitors which is needed for the stable operation of the converter.

In recent years STATCOMs with grid forming controls are being acquired by TSOs, and the first grid forming STATCOM unit has been put into operation in 2022 [A-21]. STATCOMs with extended storage are proposed to integrate dedicated short-term electrical energy storage, such as supercapacitors.

The energy storage is typically in the range of providing nominal power for up to a few seconds, e.g. 1s, 2s [A-21, A-3].

Grid forming controlled STATCOMS (with or without extended storage) are shown to be capable of providing amplitude jump power, phase jump power and can withstand short-circuit level jumps [A-21, A-3]. Grid forming controlled STATCOMS (with or without extended storage) can also assist system restoration by providing voltage support. In addition, grid forming controlled STATCOMS with extended storage can maintain stable operation during islanding until its energy storage is exhausted. In small power systems (e.g. islands) with distributed energy generation, such functionality could potentially help the system to ride through an islanding event as it creates a voltage source for the distributed energy generation to reconnect.

Grid forming controlled STATCOMs with extended energy storage are shown to be capable of providing inertia power [A-3, A-21]. However, the inertia power (current) is limited by the converter and energy storage’s current limitations, and the amount of total inertia power is inherently limited by the energy storage capability of the supercapacitors. In order to utilize the energy stored in the super capacitors, the DC link voltage can be controlled to a much lower level. In addition to the underlying grid forming control, changes in DC link voltage control may be required to fully utilize the energy stored in the super capacitors. In the literature, STATCOMs with extended storage are proposed using full-bridge MMC technologies, so that it is theoretically possible to control the DC link voltage as low as zero [A-3, A-4]. However, in practice, the DC voltage may be controlled to a certain level to prevent shortening the lifetime of the supercapacitors. If half-bridge submodules are used for such applications, the operation range of the DC link voltage is limited by modulation index.

Control Capabilities

The state-of-the-art STATCOM controllers are designed based on the assumption of a strong AC system, thus adopting grid-following control strategies. Both classical STATCOMs and STATCOMs with extend storage can adopt grid forming controls to provide phase jump power, amplitude jump power and withstand short-circuit level jumps. STATCOMs with extended storage may be able to provide added benefit of prevent blackouts during islanding for small power systems. With full-bridge MMC technology, STATCOMs with extended storage can be controlled to fully utilize the energy storage, as full-bridge MMCs allow for DC voltage control independently from AC side voltages.

A.1.3.2 Synchronous condensers (SynCons)

Hardware and Primary Source Characteristics

Synchronous condensers, just like SPGMs are units that work in synchronism with the grid, not that are “synchronized” to the grid via power electronics. Any modification in the grid frequency, will imply a modification in the spinning speed of the unit. Synchronous condensers are machines that are not connected to any application (they are not motors), nor to any turbine (they are not generators), therefore, they do not have the capability to inject and maintain active power.

Synchronous condensers contribute inherently to voltage and frequency stability. They will support the frequency with their inertia, and the voltage with their short circuit power (internal voltage source (EMF) behind an impedance in addition to regulating reactive power by varying the excitation current).

Any sudden change of the frequency (RoCoF), will have an impact in the spinning speed of the rotor, this speed modification will imply a modification of the rotating energy of the unit (MJ). The change in kinetic energy will be injected to the grid (in case of deceleration), or absorbed from the grid (in case of acceleration), and this flow of power will have a stabilizing effect to the change of the power grid’s frequency.

In case of a local active power step change, the resulting phase angle change will lead to an immediate active power flow (inertia power) from the Synchronous machine, leading to a change in rotating speed.

In the same way, in case of a sudden low voltage event, the unit will inject reactive power to the grid, as this event will be seen as a short circuit. The injection of reactive power will support the voltage, and will try to minimize the low voltage event. In case the disturbance extends in time, and if the control of the unit is a high initial response device (HIR according to IEEE 421.1), there will be the possibility to start to inject reactive power in a more maintained way and thus maintain voltage control and stability during long low voltage events.

In both cases, the action of the unit will be supplied instantaneously and there is no need to have a control device to operate the unit in this way. The unit itself will operate in this way, based on its own natural (inertia of the rotating masses (rotating energy) and the sub-transient reactance). That is why synchronous condensers have the capability of supporting the frequency and voltage of the grid.

In case of low inertia grids, there is the possibility to attach a flywheel to the synchronous condenser to increase the inertia of the unit. Flywheels are massive cylinders of steel that are attached to the main shaft of the unit. The unit will have higher kinetic energy, but also there will be an increase of the mechanical losses of the unit. In some cases the flywheel will be spinning in a vacuum chamber in order to minimize these losses. As the unit will have a high inertia, the stopping time of the unit will be also increased, having an impact in the design of the complete plant.

LFSM modes (-U underfrequency, -O overfrequency) are activated after all frequency containment reserve resources are fully deployed, and it is requested to increase/decrease active power. Synchronous condensers do not have an energy source that can be controlled to increase or decrease its output power, so to our best understanding it cannot be considered as an LFSM controllable unit. Synchronous condensers' active power is "stored" as inertia, and this inertia is used in "real time" as a resource to charge/discharge energy in a rotating form, but not controllable, so cannot be activated in LFSM modes.

Control Capabilities

A synchronous condenser with an automatic voltage regulator (AVR), has the capability to control the voltage continuously. By modifying the excitation of the unit by the AVR, the, synchronous condensers have the capability to inject or absorb reactive power from the grid.

With the controlled injection or absorption of reactive power, the voltage will be controlled and modified to the setpoint of the Automatic Voltage Regulator (AVR).

It is very important to have a HIR AVR, in order to have a fast excitation response to meet system requirements (especially with regard to low voltage events).

It is also possible to include a power system stabilizer (PSS) in the AVR. The PSS improves the stability of operation of the units during low voltage fault ride through.

A.1.3.3 Electricity Storage Modules and Electric Vehicles (V2G)

Hardware and Primary Source Characteristics

Battery electric storage systems (BESS) as a type of electricity storage module are usually connected to the grid via converter systems similar to PV inverters. The most important difference is the bidirectional active power capability, leading to slightly different power electronic topologies and thermal design for the semiconductors due to the different current loadings. For most applications (except e.g. for very small Island applications of a few kW), there is usually no value and need for overloading capability, especially in energy applications.

The batteries can be characterized depending on their power-to-energy ratio which is usually selected depending on the applications. Lithium ion based batteries are so far the most used technology in stationary storage applications thanks to their high performance both in power and energy capacity. Projects up to scales of hundreds of MW have been installed, essentially as hybrid production installations with renewable sources such as PV and wind.

The battery's I/V curve is quite linear within normal operation limits. The inverter will operate the DC-side at the desired operating point, with a similar and even more robust dynamic capabilities compared to a PV inverter, since a matching operating point on the battery's I/V curve is much easier to find than on a PV generator's nonlinear curve.

Also the DC link is designed with criteria similar to the one of a PV Inverter (electromagnetic-interference performance, lifetime, quasi-stationary voltage ripple limitation). Due to the battery's long term storage capacity and capability of immediate provision of active power, BESS are very well suited to provide *phase jump power* and *inertia power*.

However, the power range and duration of providing phase jump power or inertia power is limited by the semiconductor's thermal constraints and the accepted short term power provision of the battery itself. Even a short-term overload capability for a few 100ms needs to be taken into design consideration in case it is required. If such a provision is to be guaranteed, the required headroom has to be taken into account during design and operation.

Peculiarities of V2G-Applications

As electric vehicles are new assets connected to the grid, some preliminary definitions are required.

- The designation of electric vehicle includes not only full battery electric vehicles but also plug-in hybrid vehicles. So, the requests for charging power are not always high power.
- Electric vehicles are not limited to passenger cars but also include trucks and busses.
- Passenger cars are not limited to privately owned vehicles but also include fleets. It should be noticed that about 50% of the sales of the cars are for fleets.
- Most of the overnight fleet charging is at less than 50 kW per vehicle, the same also applies for busses.
- The term of V2G, in general, defines the capability of an electric vehicle associated with and Electric Vehicle Supply Equipment (EVSE) also named charging station to manage bidirectional power transfer between the battery of the electric vehicle and the grid. It encompasses a lot of variants such as:
    - V2L (vehicle-to-load) where an electric equipment is directly connected to the vehicle inlet dedicated to EV charging and supplied as a standalone power generator will have done. In V2L, the EV already acts as a grid forming (but not connected in parallel to the grid),
    - V2H (vehicle-to-home) where the electric vehicle will supply power to a grid islanded home or part of the home thanks to subpanels to which emergency electrical loads will be connected in accordance to the max power that the Electric Vehicle is capable of. In this case also, the electric vehicle associated with its EVSE acts as a grid forming (but not connected in parallel to the grid)
    - V2G (vehicle-to-grid) is often considered as the association of the EV+EVSE delivering energy back to the network in a grid following mode with power limited to the one consumed by the local electric loads connected below the meter (non-

export mode) or with a power exceeding the one that the electric loads consume and then exporting part of the generated power to the Public Network.

- The term V2X is sometimes used to mean all of the above.
  - DC chargers are often considered to be limited to high power charging (i.e. over 50 kW) but the majority of existing V2H applications are using bidirectional DC chargers in the range of 3 to 7 kW.

Most of high- power charging stations use multiple modules interlaced in the time domain to improve their efficiency at partial loads and the cost trade-off. The use of high-power chargers for V2G seem very limited today as most of their uses are linked on on-road charging and therefore, the EVs stay connected only for the duration of their charging before continuing on their way, so few of them are expecting to become bidirectional.

Topologies of the converters used to charge and discharge of electric vehicles are very similar to the ones used for PV and electricity storage system (ESS) application. So far, there are no main technical differences between the designs of onboard and offboard bidirectional chargers especially at power ratings below 22 kW. Offboard chargers are often preferred for reasons linked to cost and grid connection rules. For future adaptation and evolution, it is easier to manage with an offboard charger compared with an onboard where any change made to the charger may lead to a re-homologation of the EV according the UNECE regulations. Even if some vehicles are already offering V2X features, new international standards will be published in the following months. For applications below 22 kW, it should be noticed a great evolution associated with new power electronic technologies which are now available such as SiC or GaN leading to new topologies, new thermal exchanges, and new controls with an increase of sampling frequencies from several tens of kilohertz up to megahertz. So, as a consequence, it should be noticed that for periods of every three years, new equipment based on new technologies are launched in the market. On another point, the increase of frequency sampling reduces the delay of control loops, increasing the dynamics of possible responses but the control loop stability remains the most important point to pay attention to. Bidirectional chargers are at their early stage of development and deployment. Multi-level topologies are increasingly used with improved features on power signal quality. The description above of PV inverters and ESS converters applies to bidirectional chargers. One possible feature for the future could be to use the EVSE as an interface with the grid and to receive some configuration parameters describing the network topology and impedance that the couple (EV+EVSE) will have to deal with and in the opposite, when the EVSE is exposed to the grid the capability of this couple which may change when a new vehicle is connected to the EVSE. From this configuration, grid forming services could be adjusted depending for instance of the energy stored in the battery, the latency in the control loop. The grid forming service will be managed by the converter wherever it will be located. Thanks to the existing ISO 15118-20 communication, data exchanges between the EVSE and the EV will take place and these exchanges for a DC interface have to be seen as an automation data exchange. V2G could be a good opportunity to develop grid forming in parallel to the grid.

It should be noticed that several companies are developing new equipment which present a single AC connection to the grid and a DC bus to which PV, ESS and EV are connected providing grid following and grid forming services for home applications. Such equipment has a high degree of controllability.

Control Capabilities

Due to the high power availability, range and dynamics of a battery, the inverter control can apply very different desired grid following and grid forming controls. In grid following modes, the capabilities with regard to LFSM performance and voltage control available today, is very similar to the capabilities of PV-inverters, but with less restrictions with regards to primary power availability. Thus, direct voltage control of battery inverters in grid following mode are not yet state of the art.

With regard to grid forming control, there have been already several implementations, investigations and commercial products. Within the design limits, all the system needs associated with a high share of PPMs can be provided. However, depending on the performance criteria for advanced capabilities, there will be development effort, e.g. in terms of desired damping capabilities.

Peculiarities of V2G-Applications

The V2G control has to be seen as very similar to the one of ESS with the unpredictability of PV (the EV user may want to drive his EV whenever he wants) and with its own constraints to be managed such as the thermal management of the battery or other internal constraint of the vehicle or vehicle usage. This comment may be relaxed when the EV are used in fleets where their use is more predictable and the thermal management also. This explains why the new equipment for homes associating PV+ESS with EV offering bidirectional power transfer in DC will provide more capabilities.

A.1.3.4 HVDC (interconnector HVDC and Offshore)

Hardware and Primary Source Characteristics

Interconnector HVDC and DC-Connected Windfarms

HVDC systems must be distinguished between (1) interconnector, which interconnects two AC systems and (2) HVDC-connected offshore wind parks, which connects an offshore wind farm to an AC system. Advanced capabilities in such a context are only referred to the capabilities that an HVDC system provides to the AC system.

Over the last decade, MMC based HVDC systems have become the most dominant technology in the market due to lower power losses, high controllability and suitability for high voltage applications [A-5, A-6]. In terms of control scheme, the majority of existing HVDC systems are operated with grid following control. However, HVDC systems with grid forming controls are becoming the preferred options particularly in the German and GB market.

For an HVDC system, the advanced capabilities can be roughly divided into (1) reactive power/ voltage regulation and (2) active power/ frequency regulation, considering that reactive power/voltage regulation is largely dependent on the HVDC converter capability, while active power/frequency regulation depends on the primary source behind the HVDC link, i.e., the other AC system or offshore wind farm.

Within the HVDC converter's design limit, an HVDC system can provide voltage amplitude jump power and short-circuit power. In case of a short-circuit in the AC system, the excessive power from the wind farm is usually taken care of by means of DC choppers.

An HVDC system with grid forming controls can provide phase jump power, inertia power and frequency support. Due to the required intrinsic energy storage within the MMC converter concept, HVDC converters are able to utilize a fraction of the energy stored in its submodules to provide nominal power within a few ms, up to a certain limit. This enables HVDC converters to provide phase jump power. However, inertia power provision and frequency support (FSM or LFSM) from an HVDC system is limited by

1. characteristics of the primary source. In the case of an interconnector, an agreement between the different system operators needs to be in place, in terms of compensation mechanisms and technical control limits. Since inertia and frequency support from one AC system to another typically entails frequency deviation of its own system. In the case of a DC connected

offshore wind park, the same limitations from the wind turbines described for an AC connected wind park apply as well.

2. HVDC converter's capability. The amount of inertia power and frequency support has to be always within the HVDC converter's capability.
3. Pre-event operating point. Similar to any power-electronics based system, the total active and reactive power of an HVDC system can provide is limited by its design limit. The "additional" active power (such as phase jump power, inertia support and frequency support) an HVDC system can provide is largely influenced by its pre-event operating point. If an HVDC system is already operating at or close to its designed capacity, the additional contribution will be very limited, without oversizing the HVDC converter or additional equipment.

Embedded HVDC systems

Inertia power and frequency support can only be provided by HVDC systems if the opposite HVDC station is able to draw/absorb additional power from the "other" AC system. For embedded HVDC systems, both HVDC stations see roughly the same frequency (or with some time delays) and no additional power can be drawn/absorbed from the same AC system. As such, embedded HVDC systems can not provide inertia power and frequency support. However, embedded HVDC systems with grid forming controls are still required be able to remain in stable control in the event of frequency variations. In the event of a system split and provided that the system conditions are still within connection limits, these HVDC systems are then required to remain in service and provide inertia and frequency support.

Control Capabilities

Up to date, the majority of the HVDC systems are operated with grid following control. Typically, one station controls the DC voltage, and the other station controls the power flow. For DC connected offshore wind parks, the offshore HVDC station is typically operated with U/F mode, controlling the offshore AC voltage amplitude and frequency. HVDC systems with grid following controls can also provide frequency support functionalities, such as LFSM and/or FSM.

Many grid forming control schemes have been proposed for HVDC converters, such as droop control [A-7], virtual synchronous machine [A-8], power synchronization control [A-9], and matching control [A-10]. Unlike synchronous machines, the "machine-like" behaviour of HVDC converters is largely dependent on the control structure and parametrization. There is flexibility in choosing the appropriate controls and parameters to achieve the desired behaviour. However, there are trade-offs in selecting the different capabilities. As an example, in order to follow a fast RoCoF, a fast "machine-like" tuning may be required while a stronger inertial support typically entails a slow "machine-like" behaviour. As a result, the requirements of these capabilities need to be coordinated so that a satisfactory overall response can be achieved.

A.2 Control capabilities of Inverter based devices

A.2.1 General

The response of a converter system will be designed for a specified set or range of parameters of the grid connection point. These parameters (e.g. impedance, short circuit level, etc.) can have a significant impact on the performance and should therefore be specified. Modification of such grid related parameters after plant commissioning should therefore be carefully agreed between the RSO and the plant operator.

When operating in an island mode (as a first contingency of the grid), another contingency scenario may not be resolved in the way it would be expected if this second contingency occurred during normal operation.

It is desired that the inverters stay passive in all operation modes/scenarios to ensure harmonic stability under widely varying operating conditions. It has been documented that the delays in the inner current loop (if implemented) including the measurement loops of the VSCs cause the converter to act as a negative impedance at higher frequencies, resulting in undamped oscillations leading to serious instability conditions. Many grid forming control implementations utilize emulation of virtual impedance, at their inner current loop control that may show negative impedance behaviour, resulting in oscillations at high frequency regions. The virtual impedance loop adds additional dynamics that may impact the passive behaviour of grid forming. The virtual impedance may be used to improve P/Q decoupling in steady-state and as a current limiting control under fault conditions.

A.2.2 State of the Art: Grid following control

The state of the art grid following converter control in parallel to the grid is to synchronize the converter to the grid voltage and feed in an appropriate level of active or reactive current (or power). This active power setpoint depends mainly on the actual active power potential of the primary source (e.g. wind speed / solar irradiation). Normal operation is in the MPP. The reduction or modulation of active power is realized by changing the operating point at the inverter’s DC side or primary power electronics conversion stages. The applicable dynamics depends on the dynamics of the primary source and electrical storage available in the power electronics topology.

The angle of the current fed in can be controlled in order to provide reactive power. Depending on the power electronics design, a high reactive power operating area capability can be achieved (down to a power factor of 0).

With decreasing short circuit ratio, stable operation of the grid following control becomes more and more challenging. The current fed in, itself affects the measured voltage’s amplitude and phase, the larger the grid’s impedance is [A-11].

Based on frequency determination by grid following controls there may be a kind of inertia emulation by evaluating the RoCof and adding an extra component to the output power setpoint. However, especially in low SCR conditions, such functionality needs to be designed carefully in order not to be susceptible to instabilities.

A.2.3 Grid forming (grid forming) Controls

Various topologies and control structure configurations of grid forming converters are presented in the literature. The objective of grid forming control structures is to maintain an internal voltage phasor that is almost constant in steady state, dynamic and transient time frame scenarios. The grid forming control must respond quickly to changes at the PCC and maintain stable control based on the grid code requirements during challenging network conditions. The voltage phasor must be controlled to maintain synchronism, and actively regulate the active and reactive current and voltage supporting the grid.

The different implementations of the grid forming control topologies exhibit strengths or weaknesses fulfilling various aspects of the technical requirements e.g. creating system voltage, contributing to fault level, contributing to system inertia, grid frequency and voltage stabilization, small signal stability damping to maintain power system stability, system restoration and black-start capability, prevent adverse control interactions, acting as a sink to counter harmonics and unbalance in system voltage.

Reference [A-12] provides a review for some of the grid forming pilot projects and demonstrators. Most of presented projects are interfaced with the medium voltage (MV) grid providing grid forming ancillary services. The reviewed pilot and test installations show that all demonstrators have so far proved to perform well and capable of achieving their objectives. However, the integration of high numbers of grid forming converters in close vicinity may have an adverse impact on the system stability resulting in undamped oscillations in the transient response after a perturbation as shown in reference [A-12]. Large integration of grid forming units distributed across a power system might introduce instability and oscillations causing critical issues in the re-synchronization process as these units may compete for synchronism with each other and in the worst cases lead to instability and blackout in the power system. In [A-13], laboratory test results of a battery storage system in grid following, grid supporting, grid forming droop and grid forming inertia mode in combination with a synchronous generator are reported.

At the moment, there are no publications presenting the impact and possible stability issues with large integration of grid forming units with various control strategies. The adjustment flexibility of grid forming control parameters is a clear advantage compared with grid following converters, however the improper selection or setting of grid forming control parameters will result in power angle oscillation and instability issues, under change of operating modes/scenarios. This is why in the grid forming projects (as well as for other new and large applications) in preparation today, extensive interaction studies are performed during the planning phase.

Generally, the control structures can be phasor controllers emulating the synchronous machine dynamic behaviour or P-f or Q-V droop controls, and non-linear controls such as virtual oscillator control. The controls are divided to outer current control calculating the phase angle ῳ, F, Q, P and amplitude of the voltage, and the inner current control producing the modulation signals, e.g. pulse width modulation of the switching semiconductors. There have been several publications on the comparison of grid forming control approaches (A-14, A-15, A-17, A-18, A-12]). According to [A-15], the grid forming control strategies can be classified to following main categories, while each category may have several subcategories or classifications:

- Droop control,
- Virtual synchronous machine (VSM),
- Enhanced direct power control (EDPC)
- Synchronverter
- Virtual oscillator control (VOC) and communication (ICT/IoT) based approach.

The primary objective of these controls is to ensure the converter voltage phasor remains almost constant in transient and sub-transient time frames, allowing the converter to immediately responding to changes at the PCC and maintain stable operation under steady state, and under contingencies e.g. symmetrical and asymmetrical fault conditions at the connected grid.

The underlying idea behind the grid forming concept is to emulate the essential behaviour of a real synchronous generator being a voltage source behind an impedance with specific synchronization capability by controlling a power electronic converter.

The grid forming approaches and concepts such as those below are provided mainly by academia. Only a few field results are known, and the detailed control concept of the OEMs involved is usually not disclosed and is subject to continuous development. Looking at recent publications and taking into account that there is as yet no industry-wide agreed standard on grid forming acceptance and performance criteria, the highest technology readiness of grid forming technology can be seen in BESS applications. For HVDC and Statcoms the application is known to be in preparation. For wind energy and PV the technology readiness with regard to grid forming remains very low.

A.2.3.1 Droop control:

The droop-based control is a phasor-domain control structure that utilizes the droop functions to control the output voltage and frequency of the grid forming converter. This type of control is mainly utilized in microgrid applications. Grid forming droop control is realized by active and reactive power droop control. The droops can have P and Q, or V and ω as their input parameters and are comparable with P-F or Q-V droop functionality.

There are different implementations of the voltage profile management loop or the droop control functionality. Examples are PI based voltage control or reactive power control for synchronous power.

Control, cascaded structure with PI control in the first stage and droop in the second stage and voltage vector control. It should be noticed that single-loop voltage control approach shows current controllability weaknesses resulting in the overcurrent conditions of the converter components consequently tripping the converter during grid faults. Hence it is recommended to utilize the dual-loop voltage and current control scheme that is commonly implemented.

A.2.3.2 Virtual Synchronous Machine (VSM):

VSM controls emulate an SGPM's response so that the grid forming converter can act as an SGPM in providing an active power response that mimics a SGPM's expected contribution to sudden changes at the PCC e.g. change of load or generation conditions or a system fault. A virtual synchronous generator which emulates a rotating synchronous generator is a straightforward control approach for a grid forming to provide both voltage and inertia required to support power system operation. The fundamentals of the VSM method lie in the swing equation with virtual inertia and damping factor. Thus, any VSM implementation contains more or less explicitly a mathematical model of a synchronous machine. The specific model of the synchronous machine and its parameters is largely an arbitrary design choice as proved by the many different solutions discussed in literature [A-19].

Grid disturbances or fluctuations impose a shift in the operation point of parallel connected VSM converters, resulting in a change in the output power and power sharing between the parallel connected grid forming generators. The P-f droop control function is therefore necessary to adjust the output frequency of an inverter to prevent the system from further increasing or decreasing its output power. This is equivalent to the response of a rotating synchronous generator to grid disturbances and the frequency adjustment alters the phase angle of the inverter voltage, which regulates its active power generation. Meanwhile, the Q-V droop control function will prevent the reactive power circulation within the parallel grid forming converters. The Q-V droop controls the magnitude of the inverter output voltage hence oscillations in the reactive power of the grid forming inverter are eliminated, and thus the circulating currents among these inverters are minimized.

A.2.3.3 Virtual Oscillator Control (VOC):

These controls mimic the self-synchronization in networks of non-linear oscillators. VOC controls behave like a non-linear oscillator with a dead zone. A VOC is a nonlinear control strategy, which makes a converter reproduce the dynamic of a weakly nonlinear limit-cycle oscillator and contribute to the grid forming converters synchronizing with each other starting from any arbitrary initial conditions, with the advantage that it does not require for any form of communication between the grid forming units. Droop control and VSM control strategies are designed in the phasor representation for voltages of grid forming converters, while the VOC is proposed in the time domain by emulating nonlinear oscillator circuits, which only use output current measurements as the oscillator input for voltage control calculations.

A.2.3.4 Synchronverters:

A synchronverter mimics synchronous generators. This control strategy requires a dedicated synchronization unit, e.g. a phase-locked loop (PLL), to provide the phase, frequency, and amplitude of the grid voltage as references. This control strategy became popular during the last decade as it can completely overcome the need for a synchronization unit both for pre-synchronization purposes, as well as and during normal operation. The control consists of a synchronization unit e.g. PLL to synchronize the converter with the grid, a power control loop to regulate the active power and reactive power exchanged at the PCC, a voltage control loop to regulate the output voltage, and a current control loop to control the current of grid forming converter.

The controller of a synchronverter has 2 channels, one controlling the active power while the other controls the reactive power. Both controls utilize a frequency droop control loop. Hence, the frequency control, voltage control, active power control, and reactive power control are all integrated in one compact controller with only four parameters. As indicated, a synchronization unit is required to provide the grid information for the synchronverter to synchronize with the grid before connection and for the synchronverter to provide the desired real and reactive powers after grid connection. However, the synchronization unit imposes drawbacks for this design. This converter topology requires a stiff DC bus voltage being supplied from a BESS or renewable energy sources.

Synchronverters utilizing PLLs or filter structures in their synchronization loops are susceptible to low SCR grid conditions [A-14, A-15, A-16].

A.2.3.5 Current limitation and fault-ride through (FRT) capability of grid forming converters

Grid forming converters synchronize with the grid according to their output active power, which is similarly to synchronous generators. In contrast to the PLL approach, the power-based synchronization of grid forming converters, together with the PCC voltage control, allows grid forming converters to maintain synchronism in low SCR grids. However, in stiff grids with high SCRs, grid forming converters tend to lose synchronism with the grid, since the slight change of the phase difference between the converter and grid voltages can lead to large active power variations. A robust damping control is thus required for converters operating in a wide range of SCR conditions.

Due to the intrinsic behaviour of a voltage source behind impedance, operation under contingencies e.g. under grid faults, unwanted converter over-currents may occur in a grid forming converter, with consequent risks for hardware damage. In addition to hardware oriented current limitation schemes, the easiest solution to overcome this critical operating condition in a grid forming converter is to switch to a vector control mode under grid fault conditions. In fact, although limiting the converter currents due to overload conditions or grid faults might seem relatively simple, ensuring the stability of a grid forming converter under such operating conditions could instead become challenging, especially when operating in parallel to standard SPGMs. As described earlier, various grid forming controls may show weaknesses under various operation scenarios, hence it is important to consider all relevant operational scenarios and stability of the converter controls, as well as interaction with nearby converters or grid components.

For a typical BESS interfaced with a grid forming converter, both, the power control and voltage control can be achieved with a single stage control, while wind and PV interfaced with grid forming converters will require at least two stages for different control actions. The wind or PV converter regulates the operation of the renewable energy sources for maximum power extraction, and the grid-side inverter regulates the DC link voltage as well as the reactive power generation defined by grid forming control functions. In this case the control priority is to maintain the proper DC link voltage interlinked to the active power supply from the grid-side inverter.

In case of close faults, grid forming converter fault currents are primarily determined by the converter controls. Converter controls limit the fault current close to maximum load values or the designed converter nominal currents. It is important to emphasize that the active current component of the fault current level is supplied largely as a result of the energy behind the converter supplied from the wind or PV generator during the grid fault incident and the fault current supplied can be lower than the nominal designed converter load current. Oversizing the converter can provide higher fault currents. However, the remaining question will be if this oversizing can be an economic and practical solution. Depending on the short term overcurrent capability, the duration of the fault overcurrent provided by converters is limited to a few cycles and then is usually limited to the maximum load current. The reduced fault currents make the conventional grid's over-current protection schemes unreliable and difficult to coordinate. In most power systems in operation, the protection functions rely on the difference between max load current and fault current for the reliable protection of the power system. In addition, most of the existing protection systems require detection of fault direction (such as directional overcurrent, distance protection). These relays require a polarizing quantity that is present with a sufficient magnitude during the fault. SPGM's supply negative or zero sequence components providing a reliable polarizing quantity. Power electronic converters based on their design may have limitations in supplying zero and negative sequence components since they may be suppressed by inverter controls or the connecting transformers.

A.2.3.6 Transition between islanded and grid-connected modes

Transition between islanded and grid-connected operation modes could involve significant deviations and oscillations due to the potential mismatch in frequency and voltage amplitude in transition from islanded mode to grid-connected mode.

Based on the grid code requirements, grid forming converters must provide a smooth transition between both operation modes. Particularly, under islanded operation mode, grid forming converters should be able to automatically establish and stabilize system frequency and voltage, while under grid-connected mode, grid forming converters must inject the required amount of active and reactive power in response to PCC changes and the grid commands. It is required that during the transition between islanded and grid connected operation mode, instabilities are avoided, and oscillations are adequately damped to provide system stability in the pre and post transition operation modes.

Seamless transition between island and grid connected operation modes has been intensively discussed in the last decade, this topic still represents a challenge for grid forming converters.

A.2.3.7 Background on phase angle changes and related power flow

Generators and inverters can be represented in a single line diagram as a voltage source behind an impedance (see Figure 1). In a synchronous generator, the voltage amplitude is defined by the rotor excitation, the voltage angle by the rotor angle. In the case of an inverter for PV, Wind Turbines, STATCOMS or HVDC, voltage amplitude and voltage angle are defined by the switching pattern of the switching elements, usually IGBTS.

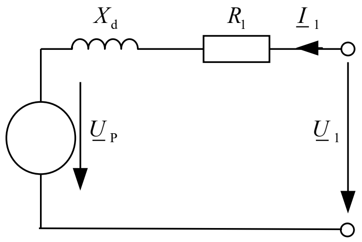

Figure 3: Single line equivalent of a generation unit.

Active power flow from generators and inverters into the grid can be approximated by

$$P = -\frac{3U_1U_P}{X_d} sin\delta, \quad \text{with} \qquad \delta = \varphi_{\mathrm{uP}} - \varphi_{\mathrm{U1}}$$

if the resistive part of the impedance is ignored.

The resulting curve is shown in figure 2. The torque (or power changes as function of voltage amplitude, voltage angle and impedance, with a maximum at a voltage angle difference of 90°.

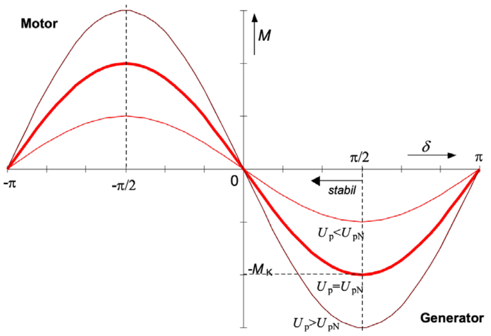

Figure 4:Torque (or power) as function of the angle delta between grid voltage and internal inverter / generator voltage.

Depending on operating mode (generator, motor, capacitive, inductive), different relations between grid voltage and inverter/generator internal voltage apply (see Figure 3)

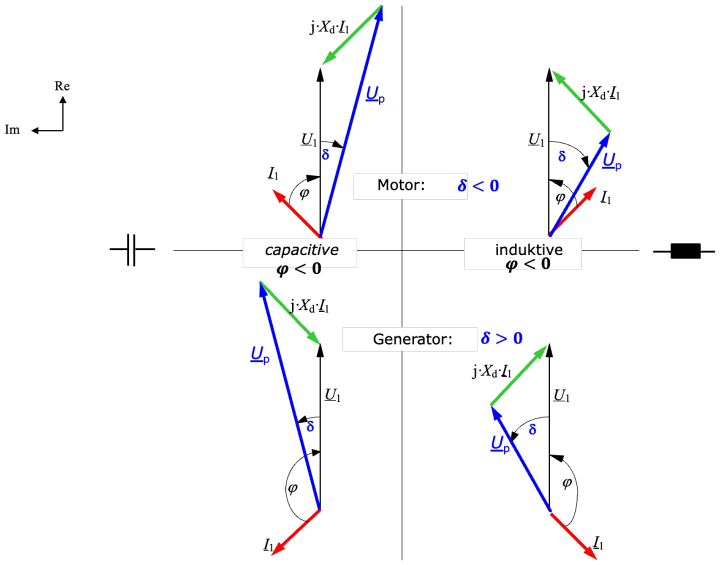

Figure 5: Inverter/Generator and grid voltage for different operating points.

A **positive phase jump** (voltage angle step change) of the grid voltage reduces voltage angle delta and therefore **reduces the active power flow**.

A **negative phase jump** (voltage angle step change) of the grid voltage increases the voltage angle and therefore increases active power flow.

For a typical inverter, an impedance X of 10% can be assumed. (For small values of delta in radians, sin(delta)=delta is a good approximation. At rated power, an inverter is operated at a voltage angle delta of 5° - 6°. A phase angle jump of the grid voltage by +6° leads to zero power, a phase angle jump by -6° leads to 2 p.u. active power, if it is not limited from the controls or the generator at the DC side.

Consequences: For an inverter, a positive phase angle jump reduces the active power flow. Storage is not necessarily required to reach this operating point. A DC link chopper or storage may be used

- if the primary side of the inverter (the other end of the DC link) cannot be controlled quickly enough to reduce the active power flow into the DC link.
- for wind turbines, to avoid a possible impact of large or repetitive changes in the power flow on the life time of the mechanical structure.

A voltage angle change of more than -1° only (an equivalent to 20% rated power) requires a fast active power curtailment by the inverter.

A.3 Support during black start and grid restoration

A.3.1 Technologies with secured primary energy source (e.g. HVDC Interconnector / battery electric storage systems)

In case of full or partial black out events, black start capability from power generating units is required to restore the power grid. Generally, sufficient primary energy, auxiliary power and control capability are required from the black start PGM to create a voltage source, maintain frequency and voltage within permissible ranges when energizing active and reactive loads, and re-synchronize to other parts of the power system.

The state of the art VSC based HVDC systems (interconnector or onshore station) can typically provide black start capability if required so [A-22, A-23]. The primary energy is supported by the live AC system (or onshore system in case of offshore links), and the black-start station is responsible for creating an AC voltage and maintaining a power island. Both AC voltage/frequency (UF) control and grid forming control are suitable in such situations to regulate the voltage and frequency of the power island. “Sequential black start” and “collective black start” (or soft-start) are the main restoration schemes as described in [A-23]. In a “sequential black start” scenario, the AC busbar of the connection point is typically brought to rated voltage, and then sequentially energizes the network elements (transformers, lines, etc.). In contrast, in a “collective black start” or soft-start scheme, all network elements to be energized are connected first and then the complete power island is energized using a voltage ramp-up. The soft-start solution typically can avoid large inrush currents and oscillations, and thus may present a more favourable solution [A-23]. Another technology which has the potential for providing black start services is battery storage system, in particular from energy availability perspective. In recent years, using BESS, several black start pilot projects have been brought to operation or under testing. This includes off-grid island systems [A-24], systems to start up gas turbine power stations that would not otherwise be black start capable, and hybrid power plants with BESS to enable black start capability [A-29]. However, many of such pilot projects are demonstrated at LV or MV level. Technology readiness of BESS for providing black start service at HV level may still need to be demonstrated.

A.3.2 Technologies with intermittent primary energy source (e.g. wind/PV)

Black start capable PV and wind farms are not yet state of the art. There have been publications on concepts for black start capable offshore windfarms [A-25] and a pilot on a black start capable onshore wind farm [A-26].

In addition, there are concepts, how wind and PV plants could be incorporated into system restoration in order to support this process by providing primary control ((L)FSM) and voltage control and can therefore increase resiliency of power systems [A-27, A-28]. Crucial for such application is that the system operator is able to access the plant’s data and has an idea of the plant’s actual active power capability (e.g. by appropriate forecast handling). With their capability to support voltage control functions and primary regulation, they can help to balance voltage and frequency during system restoration. However, it may be favourable that the plants operate in special operational modes (e.g. modified droops) during such conditions.

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