WP3 - Control and Operation of a Grid with 100 % Converter-Based Devices

Deliverable 3.6: Requirement guidelines for operating a grid with 100% power electronic devices.

Authors: Thibault PREVOST, Guillaume DENIS
Date: December 20, 2019
Contact: thibault.prevost@rte-france.com, guillaume.denis@rte-france.com
Contents

1 Introduction .................................................. 5
   1.1 Toward 100% PE system ............................. 5

2 Grid-forming definition for Power Electronic based power system ....... 7
   2.1 Recall on system needs .............................. 7
   2.2 Functional description of Grid-forming ............... 7
   2.3 Technical implication of grid-forming function .......... 9

3 Characterization and validation of grid-forming function ................. 14
   3.1 Motivation for external quantification ................. 14
   3.2 Time domain voltage and frequency profiles ............ 16
   3.3 Frequency domain small-signal profile ................. 18
   3.4 Link with other grid-forming approaches out of MIGRATE 19

4 Technological feasibility of grid forming with a VSC .................. 21
   4.1 Challenges of grid forming constructive capability for VSC .... 21
   4.2 Protection of grid-forming VSC against overcurrent ....... 21
   4.3 DC storage sizing for VSC in grid-forming .............. 22

5 System wide operating rules of 100% Power Electronics (PE) ........... 26
   5.1 Operating rules that would not change .................. 26
   5.2 New system dynamics indicators in PE based system ....... 26
   5.3 New ancillary services adapted to PE dynamic .......... 29

6 New simulation models for 100% PE ................................ 32
   6.1 New simulation tool ................................... 32

7 Smooth transition toward 100% PE power system ........................ 33
   7.1 Grid-forming converters contribute positively to low inertia systems 33
   7.2 The high short circuit current contribution of PE-based system .... 34
   7.3 Roadmap for transition ............................... 36

8 Summary & Conclusion .......................................... 37
Disclaimer
The information, documentation and figures in this deliverable are written by the MI-
GRATE project consortium under EC grant agreement 691800 and do not necessarily
reflect the views of the European Commission. The European Commission is not liable
for any use that may be made of the information contained herein.

Dissemination level

<table>
<thead>
<tr>
<th>Public</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Restricted to other programme participants (including the Commission Services)</td>
<td></td>
</tr>
<tr>
<td>Restricted to bodies determined by the MIGRATE project</td>
<td></td>
</tr>
<tr>
<td>Confidential to MIGRATE project and Commission Services</td>
<td></td>
</tr>
</tbody>
</table>
Acronyms

AC  Alternative Current. 38
DC  Direct Current. 38
FSM  Frequency Sensitive Mode. 10
GFol  Grid-Following. 7, 9, 13, 14, 24, 27, 31, 33, 34, 37
GFor  Grid-Forming. 5, 7, 14, 16, 22, 24, 31, 33, 34, 36, 38
LFDD  Low Frequency Demand Disconnection. 10
LFSM  Limited Frequency Sensitive Mode. 10
PE  Power Electronics. 2, 5, 7, 26, 29, 32, 34, 36, 38
PEIG  Power Electronics Interfaced Generation. 5
PSS  Power System Stabilizer. 13, 34
RoCoF  Rate of Change of Frequency. 10, 11, 33
SM  Synchronous Machine. 5, 7, 9, 13, 14, 16, 17, 19, 26, 29, 31, 33, 34, 37
VA  Volt-Ampere. 37
VSC  Voltage Source Converter. 7, 19, 21, 22, 24, 37
W  Watt. 37
1 Introduction

1.1 Toward 100% PE system

The work achieved within Migrate WP3 and presented in [1][2][3] has demonstrated that operating a transmission grid without Synchronous Machine (SM) is feasible. A direct outcome of this result is that a large scale power system only fed by Photovoltaic and Wind energy sources (also known as Power Electronics Interfaced Generation (PEIG)) can potentially be viable, provided that new operating rules are defined. In an inverter-based power system, some converters must exhibit a specific behavior to guarantee the global stability of the whole system in a short timescale. To this aim, these inverters are required to fulfill, at least, a list of necessary conditions, and are called Grid-Forming (GFor). The present deliverable details these necessary conditions that turn the inverters into the leaders of the grid dynamics.

The GFor function of inverters will give to the system its spontaneous and short term dynamic. The spontaneous and short term dynamic cover all the responses of electrical quantities following a grid-disturbance, such as a power imbalance or a grid fault. Consequently, the GFor function considers a time frame starting from zero second after an event, until some time $T_{GF}$ (the "surviving period"), when the first flexibility levers activate themself to redispatch power flows according to the observation of system state. This definition has two major implications. First, the GFor is then defined as the fundamental feature that allows a 100% PE system to survive any grid change by reaching afterwards a new stable and acceptable operating point in a finite time, shorter than $T_{GF}$. Second, the GFor definition assumes that load adequacy is always reached after $T_{GF}$. This second point implies that enough energy is available on the grid to feed the load, and that proper planning and control mechanisms are designed to balance production and consumption at any time scale longer than $T_{GF}$.

To the present day, the synchronous generators ruled the spontaneous and short term system dynamic though their electromechanical properties inherited from their physical design. The transmission system operators had historically coped with the imposed dynamic of synchronous generators, but also benefited from their rather uniform known behavior. Such that there has never been any need to define grid-codes for short-term dynamics. With Power Electronics that are controllable up to very short time-scale, this latter need is arising.

Structure of the deliverable The deliverable tackles the aspects of 100% Power Electronics (PE) systems, from the local function of the sources to the system-wide operation conditions. First, it describes the GFor function of inverter based sources from system needs and the technical implication required to comply with the physics of the network and of the sources. Then, the characterization of such inverters will be detailed, to assess if it is possible to classify, using different techniques, an inverter without precise knowledge of its control. In the fourth section, technical feasibility of such a technology will be discussed, to see how mature this technology could be. In the following section, the system operation of a grid without SM will be investigated, some rules will need to be
adapted whereas some other will stay as they presently are. Then, the need for new simulation techniques and tools will be described before evaluating how smooth the transition from present situation to the 100% PE situation can be.
2 Grid-forming definition for Power Electronic based power system

The WP3 of MIGRATE proposed to build from scratch a system only fed by power-electronic interfaced sources in order to assess the necessary conditions to operate a transmission grid without any synchronous generators [4], for any generation mix, and according to the fundamental system needs described in D3.1 of WP3 [5].

These system level operating conditions can only be met if at least some Voltage Source Converters (Voltage Source Converter (VSC)) of sufficient capability carry the so-called Grid-Forming (GFor) function in the system. The properties and quantitative requirements of the GFor function are detailed in this section.

Then the definition of GFor converters proposed in the WP3 derives from operating conditions of a large scale system. The definition might differ from other studies applied in different contexts such as Microgrids, Offshore farms, Uninterruptible Power supply (see [5] for extensive literature review). Though, common feature and link with the scientific background is highlighted in the last part of the section.

2.1 Recall on system needs

The WP3 of MIGRATE gave the opportunity to question what we fundamentally expect from a grid and therefore necessary consequences on electrical sources requirements. Power electronic devices are fully controllable, but still suffer from technical limitation. Indeed, the ideal sources described in left hand side of fig. 1 would face practical impossibilities listed on the right hand side. A resulting description of fundamental system needs have been drawn in deliverable D3.1 of WP3 [5]. The analysis of GFor requirements have then be investigated by the academic partners with the work separation of fig. 1.

2.2 Functional description of Grid-forming

The high level definition of GFor for 100% Power Electronics (PE) is derived from the fundamental system needs and technical limitation of VSC devices as described in D3.1 [5]. In such systems, the GFor converters are responsible for the spontaneous and short term dynamic of the system. In other words, in the time scale ranging from 0 to $T_{GF}$ (few seconds) the GFor converters are required:

- to behave as a voltage source,
- to be synchronized with other GFor sources,
- to operate in standalone after seamless islanding,
- to smartly limit the output current magnitude, to protect the hardware
- to be compatible with all devices connected presently on the power system, especially Synchronous Machine (SM) and Grid-Following (GFor).
The role of GFor converters is to reach a stable and acceptable steady-state in a finite time $T_{GF}$ after an event. After $T_{GF}$, other automatic mechanisms can come into play to contribute to the system stability, restore margins and energy reserves or optimize the power flow dispatch.

Note that the GFor function was derived from converter-based system, but the resulting definition is meant to be technology agnostic. Thus, synchronous condenser, synchronous loads, or synchronous generation can be compliant with the GFor function.

2.2.1 The voltage source requirement

Loads require proper voltage waveform with RMS value of voltage magnitude and frequency close to the nominal. In case of change in the load, its power consumption will only be instantaneously met if the voltage at the load terminal is maintained. In other words, as seen from the load, the grid must have a voltage source behavior in order not to fluctuate following any reasonable disturbance. The voltage source behavior is inherited from the electrical source behavior of the grid.

2.2.2 The synchronization requirement

To be able to operate a transmission grid securely, the source that are responsible for stability (GFor units) must be replicated at different location of the grid, and thus be
synchronized at the same frequency. Otherwise, the grid will be subject to big power oscillations. Also, synchronization of sources is a prerequisite for exchanging power and thus the synchronization of GFor units must be reached before $T_{GF}$ without any critical distant communication to avoid the multiplication of critical pathways.

2.2.3 Seamless standalone operation after islanding

As a principle, the operation of any part of the grid with one GFor unit should be possible if the load adequacy can be met after $T_{GF}$ (provided that the GFor size is enough for the islanded area). The standalone requirement implies that the GFor converter should not rely on any external frequency measurement (that could be provided by another GFor unit) to be stable. The transition from grid connected to grid islanded mode should be done seamlessly, no indicators such as breaker/switch position should be used.

The procedure for reconnection of two islanded areas will then be similar to present with synchrocoupling operation.

2.2.4 Control the voltage as much as possible when the current is limited

During grid transient, maintaining the voltage at the converter output would usually lead to high current flowing through the valves. Because power-electronic hardware cost is directly related to its overcurrent capability and as the aim of the project is to have a stable system while keeping the cost under control, it is necessary to allow the converter to derogate from ideal voltage source behaviour during the fault or other tough transients of the grid, as long as it does not rely on control switching action. The current limitation strategic bias states there is no identified need for feeding transients with overcurrent. In opposition, the oversizing strategy promoted in gets rid of current limitation but at the expense of 50 % over cost for no additional feature. The condition of no control switches comes from difficulty to elaborate stability proof when the control switch from one to another based on grid quantities observation.

2.2.5 Backwards compatibility

As the transmission system is composed of thousand of devices being worth billions of euros, the target situation must be reached in a smooth transition making best use of the present component. Situation without SM will be likely to first occur for limited amount of time, therefore the system cannot switch off and on at each transition. A smooth transition can only be possible if the GFor controls are compatible with all other components of the grid, especially other generation units like SM or GFol inverters.

2.3 Technical implication of grid-forming function

The present section gives a synthesis of the technical implication after analysis of the GFor function during the past four years. The objective is to give the reader the technical insights and related order of magnitude in order to accommodate future grid codes. The developed solutions within WP3 will only serve as example.
2.3.1 Description of the surviving period within grid-forming source must maintain the grid

The period $T_{GF}$ in which the system must survive on its own thanks to the GFor units is bounded in its lower and upper value. On one side, $T_{GF}$ should be sufficiently high so that the electrical transients vanishes. This ensures to reach steady state. On the other side, the system must hold the steady-state until others flexibility levers reconfigure the power flows according to sources capacities, security rules and economical dispatch.

This period $T_{GF}$ was historically in the range of 1 to 10 seconds, where the spontaneous dynamics of the system was established by physical laws of synchronous generators design. Thus, there were no needs for addressing this behavior within the present grid codes. Indeed, all synchronous generation were behaving similarly almost following the same trend from the system point of view.

2.3.2 A stiff voltage source with limited amplitude and frequency dynamics

Behaving as a voltage source means that both voltage amplitude and frequency have limited sensitivity to demanded current. The reasons for having stiff voltage sources are fourfold. First the stability of interconnected GFor sources requires voltage magnitude and frequency to be independent and with limited dynamics. Secondly, to be quickly measurable by other devices, the grid quantities must have limited variation within a reasonable measurement window to give accurate estimation. Third, plenty of presently connected devices are controlled on the assumption that grid-voltage is not sensitive to current variation (stiff grid). This character must be maintained in the future. Fourthly, power quality issues require stiff voltage to limit the flicker. Power-electronic loads of poor quality are indeed sensitive to flicker.

According to the GFor definition the inverters controls have to be stable even without telecommunication available. Therefore, to synchronize on the grid, they use the electrical quantities as a telecommunication channel. As it has been demonstrated in 2.2.4 of [2] that to achieve stability of a system with only GFor inverters, they should not try to make the frequency vary faster than the line dynamics. This will allow other inverter to ”see” the frequency change and synchronize. Therefore, even if the converters can change their frequency reference very quickly, stability can be achieved only with a slowly varying frequency.

Regarding the frequency variation, the limiting criteria is related to measurability of the frequency\(^1\). In this deliverable, we assumed that a RoCoF below 2Hz/sec is necessary to ensure that any frequency measurement device will be able to accurately measure frequency. Even if inverters could handle faster RoCoF, and system could be stable, we have to keep in mind that the electrical system is also composed of other components that will measure the frequency, and that could in specific case help the system depending on frequency value (Frequency Sensitive Mode (FSM), Limited Frequency Sensitive Mode (LFSM) or even Low Frequency Demand Disconnection (LFDD). Therefore, we must

\(^1\)Specific protection scheme uses Rate of Change of Frequency (RoCoF) as an indicator for loss of main, but as a first step they have been disregarded, as research is ongoing to try to use other indicator
allow for frequency to be accurately measured, in this case, the higher the RoCoF, the less accurate the value. Having this 2Hz/sec, will allow other grid following unit to precisely measure frequency and for example to participate in frequency regulation. These grid following units will not help regarding the RoCoF but will help to limit the frequency Nadir.

2.3.3 The expected behavior of grid-forming sources during fault

During fault, a GFor source is expected to always remain connected, to feed the grid with demanded current in the limit of its rated capability, and to come back to acceptable operating point once the fault is cleared, without any distant information on grid voltage or breaker status. This fault ride through capability can be regarded as generic transient stability definition.

To feed the grid with the demanded current, a GFor inverter must be kept under voltage waveform control. In this condition, the GFor inverter will spontaneously feed the grid with reactive current during faults to maintain the voltage. There is no need to prioritize the reactive current over the active current, the voltage control will naturally reach the optimal distribution.

To stay below its rated current, a dedicated control strategy must be implemented once limitation is reached. The voltage source behavior can be degraded during the fault duration (decreased voltage reference, decreased voltage stiffness) as long as the device remains connected and can recover after the fault, even if the grid is separated. For this reason, the use of control switch is not recommended (moreover, asymptotic stability switched system might be undecidable [8]). Indeed keeping current control during the whole fault duration lead to instability and resonances at the filter as illustrated in III.2.2 of [1] and recalled on fig 2.

Figure 2: Illustration of misbehavior of current control during fault

In [9] and [1] a current limiting strategy based on threshold virtual impedance, decreases the voltage source reference and stiffness during most of the fault duration and
thus keeps the current in a reasonable envelope.

2.3.4 Harmonics

Harmonics have not been studied within MIGRATE WP3, nevertheless, the knowledge that we have from GFor inverters allows us to say that:

- as a voltage source GFor inverters will provide harmonic current if it is needed by the load
- this harmonic current will decrease the amount of available current from the IGBT for nominal frequency current, therefore, specific control scheme must be added to limit the amount of harmonic current.
- harmonic current sharing should be studied, in a similar way to frequency droop control, the additional burden of providing harmonic current should be shared.
- the higher the order of the harmonics, the less they "travel" on the grid (due to the impedance of grid element that linearly vary with frequency), therefore, for high harmonics "local” inverter(s) should participate more.

In this paragraph, the harmonics are not the harmonics created by the switching of the IGBT, which are assumed to be filtered by appropriate design of the filter, and depends on the VSC technology.

2.3.5 Unbalanced condition

Similarly to harmonic behavior, GFor inverters as developed in this work package applies balanced voltage and spontaneously provide any unbalanced load with unbalanced current. Unbalanced currents might cause one inverter phase to reach its maximum current capability, activate the current limiting strategy, and degrade all three phases. On the top of the fundamental function described in this section, a dedicated outer loop can be used to limit the unbalanced current by distorting the perfectly balanced voltage into unbalanced voltage when the current reaches any hardware limit. This control can be used only for steady state unbalance, as sequence decomposition requires time to be done and will have insufficient results under very fast transients [10].

2.3.6 Interaction with other components

The role of GFor inverters is to give the grid its voltage source behavior. Thus, each GFor source inherently affects the whole power system dynamic. Contrary to information technology systems, where only telecommunication flows, the plug and play property, cannot unfortunately be achieved on a transmission system. More largely on a transmission system, many units of different kinds are connected at different locations and it is not possible to prevent interactions from happening. The mitigation of interactions is complex as the cause often involves many separated devices.
Though, we can formulate the following recommendations to prevent adverser interactions or to make them easier to predict:

- to have a simple and uniform behaviour over all source,
- to ensure voltage stiffness to stabilize devices (as explained in section 2.3.2),
- to ensure damping of local interaction, usually at high frequency. Local conditions can be known and evolve less with time (using for example frequency scan [11]),
- to require the system to be passive at low frequency, a passive device can interact, but will always lead to damped phenomena. The passivity of the elements has cumulative property, which means that a system composed of passive element will be passive [12].

Theoretical proof of stability can be achieved on a system, but only if the controllers are perfectly known, as an example, the DVOC in [2] was developed to ensure global stability within specific hypothesis [13][14]. These specifics hypothesis are eventually well know by power system engineers, and are such as ”flow should not be too close to maximum power flow”, ”lines shouldn’t be too long”... As it appeared during creation of the interconnected European system, the connection of several units over very long distance led to oscillations, that were cancelled using outer loop on [SM] named Power System Stabilizer (PSS). The boundary between the local and global phenomena, as well as the frequency of such events needs detailed study. A full power-electronics power system has two advantages: the parameters of the controls can easily be adapted to mitigate a new observed instability [15], and the behavior is fully predictable from the control as there are no physical parts involved. As an example, the replica of the controls of the inverter can be used for interaction and local oscillation study, similarly to what was done in [16].
3 Characterization and validation of grid-forming function

The definition of Grid-Forming (GFor) that has been proposed in the previous section gathers the necessary conditions for a stable inverter-based system operation. Nevertheless, the definition is still high level and not quantified. To leave room for manufacturers and research centers to develop their own solutions and algorithms a qualification framework must validate if a controlled inverter is GFor.

This framework will be used by system operators to validate the GFor behavior from the point of common coupling without knowledge of its control. Motivations for external characterization are discussed first, then two approaches are proposed for GFor property quantification: a time domain method, and a frequency domain method.

3.1 Motivation for external quantification

Transient behavior of Synchronous Machine (SM) was never specified in grid codes as it was mainly driven by their physical parameters. As we have demonstrated in the previous paragraph, the transient behaviour of inverter is what will distinguish GFor from Grid-Following (GFol) inverter. In this WP, different controls ( frequency droop [17], Dispatchable Virtual Oscillator [14] and Matching Control [18] ), that were conceived in very different ways, are GFor and many others in the literature claim to be GFor: Virtual Synchronous Machine [19] [20], Angle Droop [21], Synchronverter [22], Power Synchronization Control [23] [24], Direct Voltage Control [25], etc. External quantification of GFor inverter would circumvent specifying one way of controlling inverters, and would leave the door open to manufacturers and university to developed new/better controls.

![Diagram](image)

Figure 3: the 3 GFor controls developed within WP3

In the simulation on the test cases that were defined in D3.1 [?] and released in open-source at [26], all controls behave in a very similar way, it therefore led us to think that their behavior can be harmonized. fig 5 and fig 6 illustrate how close the behavior of the three controls are.

AC signals of a single converter connected to a strong grid (SCR=20). The voltage reference is set to $V^* = 0.95p.u.$ at $t = 0.5s$, $V^* = 1.05p.u.$ at $t = 1s$, and $V^* = 1p.u.$ at $t = 1.5s$. Moreover, the active power reference is changed to $P^* = 1000MW$ at $t = 2s$, $P^* = -1000MW$ at $t = 3s$, and $P^* = 0MW$ at $t = 4s$. 
Figure 4: Single bus case study used to verify the ability to track references when connected to a strong grid.

Figure 5: Active and reactive power of a single converter connected to a strong grid (SCR=20)
These developed models, also proved to be interoperable all together when connected to the same grid [1] [2] and also with SM [27].

3.2 Time domain voltage and frequency profiles

Time domain voltage and frequency profiles will certify GFor characteristic if the frequency and voltage magnitude quantities stay within the specified domain following a deterministic grid current step. Amongst the test-cases studied in MIGRATE to tune GFor controls, two are determinant for small-signal behavior and two other for large-signal behavior.

3.2.1 Time domain small-signal profile

In order to assess voltage source behaviour, load connection test should be carried out in such a way that no limitation are hit during the connection. Hence, a load step of 10% of the nominal apparent power of the inverter is proposed. During this load connection the voltage amplitude and frequency should stay above the following diagrams of fig. 7 and fig. 8.²

²Presently grid codes require the units to stay connected for any voltage above such kind of profile, but do not require the voltage to be above a profile for a specific event.
grid codes, as the behavior of any SM is very similar following such an event, as it is only driven by the physical parameters of the machine.

Figure 7: Example of voltage profile that could be required to respect for load connection.

Figure 8: Example of frequency profile that could be required to respect for load connection.

The load size was explicitly chosen with a MVA size, the loads can be in such a wide variety of types that having the requirement only for one type of load would not be representative. A selection of specific load models (impedance, ZIP, induction machine, grid-following type), should be defined with an associated profile for each.

3.2.2 Time domain large-signal profile

The simulations presented above will not be sufficient to explicitly characterize GFor behavior, other characteristics of GFor inverter needs to be tested:

- islanding / connection test
- overcurrent limitation test (transiently with (series) inductance that is shunted)
3.3 Frequency domain small-signal profile

Because of the chosen load model or the load available experimentally, an ideal load step might not be possible. Instead, frequency based characterization offers full information of the controlled inverter behaviour. Also frequency characterization is often used to predict future adverse interaction.

It was stated that the GFor inverter will have a limited dynamic regarding frequency and voltage amplitude variation, they are bringing inertia to the electrical system. Such a property can be evaluated using a transfer function between a parameter of the system and the generated voltage waveform. As an example [28] uses the transfer function of grid frequency over the inverter frequency.

\[
TF = \frac{F_{\text{network}}}{F_{\text{Gfor}}}
\]

As an interesting result, the bode plot on fig 9 of the TF illustrates the desired behavior. Such GFor control must have a slow frequency variation.

![Bode plot of transfer function]

Figure 9: Gain of the transfer function for different inverter controls

Other transfer functions could be used to assess the GFor behavior and complete the frequency characterization presented here. Some other examples are given in [29].
3.4 Link with other grid-forming approaches out of MIGRATE

The growing interest around GFor has led to several definition attempts anterior or contemporary to the MIGRATE project. These alternative definitions of GFor or design of GFor controls are listed and compared to MIGRATE definitions.

3.4.1 Historical definition of grid-forming and V/f control

The GFor algorithms have been studied in the context of

- microgrid [31][32][33]
- offshore wind farm
- UPS, (uninterruptible power supply)
- Black-start [16]

In these four applications "GFor" Voltage Source Converter (VSC) was a synonym of "V/f controlled" VSC. It described the use of a VSC as the only voltage reference, operating at fix voltage magnitude and frequency, in a master-slave configuration of the grid. Such V/f controlled converters are not meant to synchronize with each others, and thus do not fall into MIGRATE’s definition of GFor for transmission system.

On top of the requirements of having a grid without SM, black start requires to have a flexible primary source to accommodate with the load that must be available for a specific period of time allowing for other units to start up. It also requires specific schemes for energization of grid component (slow rise of voltage), possibility to connect different sources over very long distance on radial network. On some other requirements, black start inverters might have less constraining requirement. GFor inverter on meshed network must withstand very high transient for example in case of line switching.

The MIGRATE project looked for a control that allow a transmission system to operate in any condition, especially in condition where no SM remain connected.

3.4.2 Distinction between grid-forming for microgrid and for transmission system

Early works concerned parallel operation of GFor in microgrids [34][35], such as remote power supply system or ship’s onboard grid.

In a nutshell, the characteristics of the transmission grid that make these applications different from MIGRATE are:

- the topology of the transmission system is meshed, leading to phase shift in the system without loss of connectivity,
- multiple units of similar size are connected,
- the topology is changing daily,
the grid has a very inductive behavior

the load to be met is always varying.

### 3.4.3 Other grid-forming definition for transmission grid application

At EPRI, the developed GFor control strategy automatically brings back frequency to its reference after a disturbance. The common frequency amongst units is given by a GPS signal and load sharing is achieved through angle droop control to handle fast transients, as the angle can vary fast. As drawbacks,

- they critically depend on an external frequency reference. The loss of the signal leads inevitably to frequency derive over the time.
- The frequency always goes back to nominal after a transient, therefore losing its nice actual property of reflecting the load balance equilibrium.
- Change in topology of the system lead to a change of active power of units, if setpoints are not adapted using telecommunication.
- All ancillary services related to frequency need to be redefined, as primary and secondary frequency control designs assumed a linear relationship between frequency deviation and load generation balance.

The angle droop control is not compliant with MIGRATE’s definition of GFor because it relies on communication and lacks of backwards compatibility with traditional power balance mechanism based on global static frequency deviation.

National grid, the UK TSO has long experience with GFor studies for transmission system operation. In their last report, recommendation for future grid code mainly focused on one technical implementation of a GFor structure in. Consequently, the report did not propose a technically agnostic definition of GFor.

Moreover, different grid code projects are asking for GFor capabilities even though it is not yet fully defined or let the opportunity to play a role in the future system services portfolio. The outcome of this WP will help them for their future work.
4 Technological feasibility of grid forming with a VSC

Voltage source converters (VSC) are presently a very mature technology, fast-acting, fully controllable, regardless of the underneath technology (2 level PWM, MMC, combination of both). The VSCs are the natural candidates for providing the Grid-Forming (GFor) function in future PE-based power system. Though, IGBT's valves are still very sensitive to overcurrent. The GFor functionality should be implementable in the technology available today to reach the maximum effectiveness at limited investment cost. This section describes how to refine the GFor requirements to be served by VSC at reasonable cost.

4.1 Challenges of grid forming constructive capability for VSC

Because they are fully controllable, the VSC have the potential to provide voltage stiffness largely superior to the one provided by synchronous generators. They can sharply control their output voltage magnitude to a fixed reference with feedback control and operate at fixed frequency (and thus provide infinite inertia). However, GFor VSC are limited on stiffness by their rated current and by their low energy reserve on the DC side. They are limited in control speed by stable synchronization requirements defined in section 2.3.2.

In other words, to have a stable grid in small-signal sense, inverter should not act too fast. A "slow" inverter cannot protect himself against hazardous from random events. There is a compromise between. The section answers the following question: can we protect the inverters transiently without control switching into grid-following? What can be a trade-off when the inverter reach its limits, in terms of voltage stiffness or stable synchronization. Also, GFor strategy has consequences on DC side, primary source dynamics and energy storage sizing.

4.2 Protection of grid-forming VSC against overcurrent

For the commercially available VSC, the overcurrent capability is limited by the hard blocking protection of the valves. It is commonly accepted that hard blocking opens the valve if the infeed of the corresponding current magnitude exceeds 1.4 per-unit for longer than one cycle. Hard blocking is not desirable because of the non deterministic consequences it has on harmonics and controllability. Therefore a current limiting strategy is defined as software algorithm that maintain the output current always below the hard blocking limits. As illustrated in part III of [1], three main transient events can lead to overcurrent through GFor converters:

1. loss of generation near by or connection of large load locally (transient load sharing),
2. line opening (angle shift), and
3. short circuit (voltage drop).
The system operator can choose to size GFor converters based on the transient events described above or on the small-signal stability requirements of power system (detailed further in section [5]). The choice has the following consequences:

- Sizing based on transient events requires for an oversizing of the inverters as it was proposed in [37]: "Typically the fault in feed is initially limited to 1.5pu reducing to 1.25pu in 80ms”.

- Sizing based on small-signal stability requires a software solution that protects the converter against transient, with the assumption that the other GFor converters will not be subject to the same overload and thus could ensure the power system stability.

In Migrate, we have chosen the latter approach, as one of the objective was to keep the cost of the technical solution as low as possible. The solution proposed in [1], and experimentally tested in lab scale hardware shows that current can be limited to any set-up point, whatever the previous operating point is [40]. In a nutshell, the scheme proposed in [1] limits the first current transient with a current limiting strategy, but has a virtual impedance loop that brings back the voltage source behavior as fast as possible by decreasing the voltage reference. This allows the current limitation to be only active during a few ms (2-5ms). Other current limitation scheme [41] also proved to be very efficient both in terms of keeping the current below the converter limits while having a continuous voltage source behavior on GFor inverters.

### 4.3 DC storage sizing for VSC in grid-forming

Within, at least, the surviving period $T_{GF}$, the GFor inverters spontaneously meet the AC grid needs with the energy available on DC side. Simulation of test case 1-A-1 from [1], illustrates the behavior of a GFor inverter in islanded mode after a load step. The AC power immediately rises and it is immediately converted to the DC side.

To absorb the transient on the DC side, the DC voltage must be controlled to be stiff by a flexible DC source. When the primary source is not dispatchable or fast enough to compensate for DC voltage drop, the addition of fast acting DC energy storage (high power capability) is essential, though the amount of stored energy is of same order of magnitude of $T_{GF}$, i.e. the time the system must survive before smart redispatch, and depending on the primary source capabilities.

In other word, the fast acting DC energy reserve is mandatory for the VSC GFor that opposes itself against the frequency variation following a grid event. The level of energy reserve with respect to the frequency smoothing capability has been estimated in [28]. In case of grid angle change, it immediately leads to power change in the inverter.

The amount of the energy reserve, necessary to behave as a low pass filter for frequency variation, can be estimated by the following consideration. For the simplified model of a voltage controlled inverter, subject to grid frequency variations slower than the nominal
Figure 10: AC current after a load step change at 1.5 sec

Figure 11: DC current after a load step change at 1.5 sec
frequency \( (\text{i.e., } \nu_\omega < \omega_n) \)

\[
P(t) = \frac{U_m U_{src} \sin(\theta_m(t) - \theta_{src}(t))}{X} \tag{1}
\]

Let’s assume that the inverter perfectly filters a frequency oscillation at a given frequency \( \nu_\omega_1 \), as illustrated on fig. 9 and that the inverter frequency is fixed at \( \omega_{inv} = \omega_n \). Further assuming the worse case where there is no power transfer initially, the phase angle difference is only provoked by the frequency variation of the voltage source. Therefore the power exchange can be re-written as follow:

\[
P(t) = \frac{U_m U_{src} \sin(-\int_0^t \omega_n A_\omega \cos(\nu_\omega t) dt)}{X} \tag{2}
\]

\[
P(t) = \frac{U_m U_{src} \sin(-\frac{\omega_n}{\nu_\omega} A_\omega \sin(\nu_\omega t))}{X} \tag{3}
\]

It is worth noting that as \( \nu_\omega > 1.5 \, \text{Hz} \) which implies \( \frac{\omega_n}{\nu_\omega} A_\omega < \frac{1}{3} \), validating the following approximation:

\[
P(t) \approx -\frac{U_m U_{src} \omega_n A_\omega \sin(\nu_\omega t)}{X} \tag{4}
\]

The amount of additional energy reserve \( \Delta \Sigma \) that is needed from the inverter to be able to filter can then be calculated based on integrating the power on half a period of the frequency oscillation.

\[
\Delta \Sigma = \int_0^{\frac{\pi}{\nu_\omega}} -\frac{U_m U_{src} \omega_n A_\omega \sin(\nu_\omega t)}{X} dt \tag{5}
\]

\[
\Delta \Sigma = 2 \frac{U_m U_{src} A_\omega \omega_n}{\nu_\omega} \tag{6}
\]

This results illustrates the foreseen fact that the smaller the cut-off frequency, the higher the energy required. Nevertheless, this numerical application doesn’t apply to the energy required for maintaining the frequency dynamic below a specified threshold after an event, as it is only valid for small signal periodical frequency changes.

4.3.1 Assessment of maturity level of grid-forming VSCs

Different applications, also named [GFor], or V-f control have been developed and tested in the past. These inverters do not fulfill all the requirements and constraints that are stated in this deliverable, but for each situation, parts of the requirements are fulfilled. This observation increases the confidence in the technological feasibility of the GFor function with commercially available VSC.

- Microgrid: A master GFor inverter can be used to synchronize different Grid-Following (GFor) inverters, and can connect and disconnect from the main grid. The microgrid is today not meshed and therefore do not put any phase jump constraint on the GFor inverter. [32] [33]
• Offshore: a master GFor inverter of several hundreds of MW is used to synchronize many smaller GFor inverter (wind turbine). Similarly to microgrid, the network is not yet meshed and there is only one GFor converter that is used. \(^3\)

• UPS: one or several GFor inverter(s) are used to power a small amount of load. The topology is known, usually not meshed,

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Lab scale demonstration</th>
<th>Microgrid</th>
<th>Offshore Wind</th>
<th>UPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage source</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Distributed control</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Phase jump robustness</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Multi MW size</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>Grid connected</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: validated characteristics of different GFor inverters

The above table illustrates that all characteristics have already been validated on different projects, there should be no major impact in developing a GFor inverter that will be multi MW size with GFor control that would fulfill all requirements. As a next step, the OSMOSE project, and especially the WP3 Ringolab Demonstrator \(^42\) will show the possibility to operate a 1 MVA inverter in GFor connected to the transmission system.

---

\(^3\) In the future, offshore grid might be meshed and therefore subject to phase shift but it is not yet the case.
5 System wide operating rules of 100 % Power Electronics (PE)

The necessary conditions of Grid-Forming (GFor) function have been demonstrated to be sufficient for the stability of a simple 3-buses system or on a reduced model of the Irish transmission system, that operate without any Synchronous Machine (SM). From full system operation, the work package 3 learned that the operation of such a system can be alike present operation, with many services that won’t change, some will have to be adapted, a few will have to be created. This section describes how the TSOs must adapt their vision of the power system, they practice or their tools to prepare the high-share of PE penetration.

5.1 Operating rules that would not change

As a non-exhaustive list of operating rules that will continue to exist without change:

- adequacy: as it has been mentioned at the very beginning of this deliverable, adequacy needs to be ensured at any time, having GFor inverter connected to the system will not change this requirement.

- voltage control: reactive capability of GFor inverter will be used in the same way as present SM or Grid-Following (GFol) inverter are, primary voltage control or even secondary voltage control schemes are fully compatible with GFor units, with low risk of interaction as their operation timescales are slow enough.

- secondary frequency control: the slow control that brings back the frequency to its nominal value will not have any interaction with GFor controls. They can be treated as any other generating unit.

Long term Voltage stability [43] of a 100%PE grid was not explicitly studied, but as reactive power capability and dynamics of SM, and GFor and GFol inverters are similar, the phenomena today and in the future should remain identical.

Behaving as GFor, especially the voltage source behavior, will make these inverters to react faster to reactive need from the grid, than GFol. The dynamic behavior of GFor to short term voltage [43] issue, will be similar to the one from SM but with lower capability due to limited overload capabilities.

5.2 New system dynamics indicators in PE based system

5.2.1 Electrical inertia

It has been shown that GFor inverters bring stiffness to the voltage waveform and particularly to its frequency, these controllers allow to limit the volatility of the frequency and therefore act as inertia. This property has been called electrical inertia, as instead
of being linked to a rotating device it is provided by a electrical energy buffer, and it is also different from what is usually called synthetic/virtual inertia [44] [45]. In deliverable 3.3 [2], it has been demonstrated that the location of electrical inertia on the grid has an impact. On top of this location issue, the minimum amount of such electrical inertia will probably be a key parameter for future system stability.

5.2.2 Minimum amount of GFor inverter for small-signal stability

Deliverable 3.4 [3] illustrated that the operation of a grid without SM requires a specific amount of GFor inverter to be present. The demonstration has been done on a reduced version of the Irish system (keeping only lines with a nominal voltage above 100kV), with a study of transient stability of such a system with a solid 3 phase fault at each node. In such a situation, the stability of the system composed of inverter, both GFor and GFol can be obtained only if the share of the latter in the generation mix is larger than 30%. i.e.: with $P_{nGFor}$, nominal power of connected GFor, $P_{nGFol}$, nominal power of GFol:

$$\frac{P_{nGFor}}{P_{nGFor} + P_{nGFol}} > 30\%$$

This value is only valid for the Irish test case and cannot be directly translated to any other system configuration, but the outcome is that the nominal power of GFor inverter will need to be higher than a percentage of the overall nominal power of inverters connected to the grid. Following D3.4, UCD is continuing its work and is showing that having GFol inverter that provide voltage support, (i.e. grid supporting inverter) can decrease the amount of necessary GFor inverter down to 20%. [46]

5.2.3 Transient stability of grid-forming VSC

Obviously, a system with 100 % power-electronic gets rid of rotor angle stability. However, the inner angle reference of the GFor converter is linked to its output active power and can derive during fault. The ability of a GFor inverter to recover smoothly after a fault can be qualified as a transient stability. This newly opened field already has some solution [47] but could certainly be completed with further work including consequences to the inductive motors or the GFol converters nearby.

5.2.4 New short-circuit power definition / Short circuit ratio

Even if inverters have limited current capability, they can have a high participation into the so called short circuit power. This short circuit power is usually used as an indicator for system strength, is equivalent to $\frac{dU}{dQ}$. When a GFor inverter is not reaching any limitation, it is behaving as a stiff voltage source behind its filter impedance when an additional load is connected to the system. Where a SM behaves as a voltage source behind its transient inductance for the same phenomena. As illustration, the short circuit current provided by a SM in fig. 12 is usually calculated as $I_{SC} \approx \frac{E_{L}}{X_{SC}}$ with $X_{SC}$ being
the short circuit impedance and equal to $X_{SC} = X_{line} + X_{transformer} + X'_d$ and $E'_d$ being the equivalent voltage source of the SM.

Figure 12: Short circuit : case of synchronous machine

The model of the SM as a voltage source behind an impedance is used for short circuit calculation but is also used for the calculation of grid voltage sensitivity to a change in current (the later being usually called voltage strength). The validity of the model through such a large variety of event is justified because the SM has almost no current limitation. The voltage strength can be evaluated as: $\frac{V_n}{I_n} \frac{\partial v_{PCC}}{\partial i_q} \approx X_{SC}$. Therefore for SM, system strength and short circuit current are correlated.

Figure 13: Short circuit : case of inverter

For an inverter, the calculation must pay specific attention to the limited available current. The model of the GFor inverter for small signal study can be equivalent to a short circuit impedance $X_{SC} = X_{line} + X_{transformer} + X_{filter}$. This model is only valid as long as the current limitation of the inverter is not reached. When the maximum current is reached, it is kept constant (in amplitude) whatever happens on the grid. When current limitation is reached: $\frac{V_n}{I_n} \frac{\partial v_{PCC}}{\partial i_q} = 0$ $\frac{V_n}{I_n} \frac{\partial v_{PCC}}{\partial i_q} \approx X_{SC}$ when not saturated.

As a conclusion, the short circuit current of GFor inverter will be roughly limited to its nominal current. But the short circuit "power" or grid strength brought by such an inverter to the system can be as high as the one from an equivalent SM depending on the filter and transformer impedance. Some recent research [48], proposes to reduce the
connection impedance to the grid, to further increase the impact of the grid forming on the system, at the cost of higher risk of saturation for similar transient.

5.3 New ancillary services adapted to PE dynamic

Frequency control is presently split between primary, secondary and tertiary (see fig. [14] with a time constant separation that was elaborated at a time where SM were driving the system.

Figure 14: Typical time scales of frequency-related dynamics in conventional power systems as well as typical time scale of frequency control that can be provided through grid converter interfaced generation [2]

As explained in 4.3, providing GFor function requires an energy buffer [28], that has fast power change capability. The amount of energy needed for this buffer depends on different characteristics:

- on the speed of the other devices (including other converter interfaced generation) on the network to respond to the change that occurred, and
- on the speed of the primary energy resource to change its power and adapt to the new demand.

**Deployment of transient grid forming control.** All the GFor controls developed within WP3 participate to the frequency regulation, as they all have (at least in small signal) a linear relationship between their active power and the frequency deviation: $P_{set} - P_{meas} = K(\omega - \omega_0)$. Its main advantage is that it immediately provides response when needed by the grid and keeps it until another device brings back the frequency to its nominal value. The main drawback is that it requires the GFor unit to have either a flexible primary source, or an energy storage with a significant amount of energy to withstand a deviation of its active power from its reference for several minutes.
Figure 15 illustrates the effort made by the transient GFor in blue, and the one made by the primary frequency control in grey. The faster the primary control, the lower the energy from the transient GFor will be. On the second part of fig. 15, we show the impact of the primary source flexibility. If the primary source can adapt its delivered power, as illustrated with the orange area, even with small and slow variation, the need for the DC side energy buffer required is reduced (illustrated as the blue area).

Figure 15: Illustration of power and energy delivered by different control and device.

Transient GFor control, even if not fully developed within the deliverables, is a GFor control that bring back the active power delivered by the inverter to its reference. An illustration can be found in control D) in [49], where a PLL is used to bring back the power to its reference. The speed of this PLL and its associated filter, will influence how fast the power goes back to normal, this should be defined with specific attention, as if the inverter does not provide additional power, it means that another device on the grid will have to. One illustration of this reference is shown in fig. 16.

This illustrates the behavior of one classic (converter 2) and one transient (converter 1) GFor inverter connected to a simple grid with symmetrical parameters. It can be seen that transiently, their behavior are the same, while the transient GFor returns to its setpoint within 0.5 sec.

Another way to achieve GFor behavior with limited amount of energy was presented
Figure 16: Response of transient Gfor (1) and Gfor to a load step change

in part 3.3 of [2]. Moreover, this new service to the grid has a dependency on its location, therefore, it is not possible to prescribe for a specific amount of inverter that should behaved as GFor. It has been illustrated in [2] as well as in [3], that the location of the GFor inverter has an impact on the system behavior. It can be roughly understood as the GFor inverter is bringing stiffness to the voltage waveform, and the more remote the GFor inverter the less impact it has. The way it will be implemented in future requirements must pay specific attention to this parameter, and a traditional European based market is probably not well suited for it.

It is also important to mention that the GFor requirement, makes some of the present requirement for GFor inverters obsolete. For instance, two requirements were written in a way to poorly mimic the SM behavior:

- reactive current injection: GFor automatically provide current when there is a fault, as for vast majority of fault the impedance seen from the inverter will be inductive, it will provide reactive current.

- virtual inertia: having a GFor control inherently opposed the inverter against any fast grid frequency variation, therefore providing electrical inertia to the system.
6 New simulation models for 100 % PE

6.1 New simulation tool

Traditionally, power system engineers have been using phasor/RMS/positive sequence approximation to analyse system stability. Such approximation has been developed in the context of a system composed almost solely of synchronous generation. With the change in the generation mix, and especially with the increasing share of Power Electronics (PE) in the system, this kind of approximation might not hold anymore\cite{50}\cite{51}. Part IV of D3.2 \cite{1}, details the difference of simulated behavior of the same reduced system but with different modeling hypothesis. It has been more detailed in \cite{52}\cite{53}\cite{54}. For a system with only PE devices, the traditional phasor approximation is not enough to have a representative behavior of the system, nevertheless, the full EMT representation as presently done for hardware connection is using too much details\footnote{models of IGBT switching, wideband line model...}, computation time would become prohibitive and the level of details required might prevent its use. A simplified EMT approach, with simple line models (like multiple PI section) and averaged models of converters gives accurate results with limited additional computational burden. As the main drivers for moving away from phasor simulation are:

- the accurate PLL representation
- the current limitation representation during transient

The full EMT representation is not needed, the aim being to study overall system stability during grid event and not specific hardware behavior during lightnings or other fast transients. A hybrid approach, as presented in \cite{54}, based on a reduction methods that preserves the physical structure and system variable and is more computationally efficient than simplified EMT offers a good trade-off between phasor and EMT.

Present tools that assess the short circuit power at a node of the network utilizing the short circuit current at this specific node might not be relevant anymore when grid forming converters will be deployed on the grid.
7 Smooth transition toward 100% Power Electronics (PE) power system

Now that the question of operating a system without Synchronous Machine (SM) has been addressed, it is important to validate the pathway to this situation. Even though a situation with no SM is a major change compared to the present situation, good hints show that the pathway can be achieved step by step in a stable way.

7.1 Grid-forming converters contribute positively to low inertia systems

In Migrate WP3 and in related publications, some studies showed that Grid-Forming (GFor) converters could positively affect the stability of remaining synchronous generators in low inertia systems. Indeed, they can bring the system faster to the steady-state, so that the synchronous generators are subject to unbalance during a shorter time. Thus, the rotor angle shift of synchronous generators is contained by the GFor converter support.

In part 3.5.6 Case study: 14 generator system of [2], and further detailed in [55], a comparison have been made of a system composed of SM and Grid-Following (GFol) inverters with virtual inertia controls, in front of a system with SM and GFor inverters. In this situation the inertia level is not very low, as it decreases from roughly 30% compared to actual situation, an optimal placement of inverters in both scenarios have been performed in order to maintain frequency and Rate of Change of Frequency (RoCoF) above specific limits. Two interesting results are identified:

- a system composed of many SM and few GFor inverter is stable, and
- GFor inverters are more efficient than GFol to keep frequency stability as fewer are required to meet the optimization goal.

The dynamics of the grid in a system with little inertia from big SM will be faster than the present one. Therefore, it could be feared that more stress will be put on the remaining SM during the transition to a system with only power electronics. In [27], it is shown on a simple system that a SM handles less and slower frequency variation following an event if the rest of the system is composed of GFor inverters, rather than SM regardless of the specific control implementation. In fact, GFor inverters react much faster than SM, and release the transient burden of the SM smoothing its output.

The stability of the transitioning future system will require more studies than the ones from a system with only power electronics. The work achieved within WP1, especially in D1.5 Part 3 Towards Transmission Systems with 100% PEIG [50], illustrated on a reduced GB transmission system, shows that a system with 60 to 90% of power electronic based generation unit can be stable with GFor controls. As explained in [57][58], the small signal stability of the system might not be reached for high penetration of GFor inverter in the system with conventional controls of SM. Indeed, as shown in fig. 17, the time scale of transient phenomena being different in the SM and in the GFor inverters, tuning
of regulation will need to be adapted. Still, on this simple system model, it has been illustrated that having GFor instead of GFol allows to push the stability limit further.

Figure 17: Timescale separation between different physical and control dynamics in a low-inertia system from [57]

The [57] illustrated that the limit of stability should not be seen as a maximum penetration of PE penetration, but as a threshold that differentiates between system dynamics driven by SM or by GFor inverter. When the penetration of PE is high enough, the dynamics are driven by the inverters and therefore the tuning of the Power System Stabilizer (PSS) of the remaining SM should be updated accordingly.

7.2 The high short circuit current contribution of PE-based system

Presently one of the drawback of inverters that is usually highlighted is their low overcurrent capability. When looking at a single inverter, it is true that the overcurrent capability is close to its nominal current, whereas SM can provide several times its nominal current. But, on average on a transmission system, inverters are connected with a low loading factor, which keeps room for increasing its current during a fault. Said otherwise, the ratio \( \frac{I_{\text{shortcircuit}}}{I_{\text{Load}}} \) might stay the same between SM and inverters. Moreover, GFor current has an instantaneous reaction to fault, and adapt its components to the fault characteristics.

To illustrate this phenomena, a statistical analysis has been carried out on 6 PV farms and 6 wind farms connected on RTE’s grid. The so called ”available power” is calculated as follows: \( S_{\text{available}} = S_{\text{connected}} - \sqrt{P^2 + Q^2} \). The plots shown below (fig 19 and fig 18) are based on one year of data (from July 2018 to July 2019).

It is observed that most of the time during the year, inverter can inject more current than their actual load current. It does not mean that more resource is available, but that inverter could provide reactive or active current in case of a voltage drop. Moreover, as it is based on statistical data, is doesn’t take into account any new requirement as ”standby” position for PV inverters during night.

It can also be highlighted that GFor inverter not only needs to be able to provide more current, but depending on the event happening on the grid, an immediate decrease of the
Figure 18: "Available power" plotted as cumulative time function

Figure 19: "Available power" as a function of produced power
power injected can be required, this will be provided by GFor inverter, even if operated at full power before the event.

7.3 Roadmap for transition

Several questions are still open regarding the roadmap for transition. GFor converters can be deployed at producers’ location or centralized in TSO substation. Operating rules must be defined in the cases when the power system is likely to change from 100 % PE to low-inertia system with some synchronous generation, from a day to another.

Beyond technical condition, economical levers will rule future deployment plan. The interest reader will have a look at [59] to deal with these questions.
8 Summary & Conclusion

After four years working on the WP3 of the MIGRATE project, the academic and TSO partners of the project have gained a strong conviction that the operation and the stability of a 100% power-electronic system is technically feasible with a limited investment.

The present deliverable is built upon the scientific material of the previous deliverables to synthesize the necessary and sufficient conditions for operating a system with no Synchronous Machine (SM). As a first outcome, the necessary conditions resulted in the definition of a Grid-Forming (GFor) function for converters that has never been specified in the grid-codes before, because the function was naturally fulfilled by synchronous generators. As seen from the grid, a GFor Voltage Source Converter (VSC) must spontaneously provide a controllable voltage source sufficiently stiff in magnitude and frequency to reach a stable and acceptable state after a reasonable time (few seconds). In other words, the dynamic of the voltage magnitude and frequency out of a GFor unit must be limited to satisfy stable interconnection with other GFor sources but also with other active devices such as Grid-Following (GFol) based generation and loads. These technical requirements are explained and quantified, in such way that they could be specified from the grid connection point through time-domain profiles or frequency-domain profiles. The external characterization approaches is the guarantee to define technically agnostic specifications in future grid-codes.

The second part of the deliverable evaluates technological feasibility of designing a GFor source with voltage source converters. A current limitation strategy is presented to keep the converter connected during faults while supporting the grid as much as possible. Besides software algorithm, GFor converters require fast-acting energy storage on the DC side to feed the grid with any demand during the short surviving period. The amount of energy reserve depends on the surviving period, the speed of primary energy source if any, and on the stability constraints on frequency dynamics.

The third part of the deliverable described the new operating rules that made previously defined GFor converters sufficient to stabilize a 100% Power Electronics (PE) power system. For the example of the reduced model of the Irish grid, the best placement of GFor lead to a stable system when 30% of connected PE capability are operating in GFor. Then, we successfully designed a small-signal stability indicator as the ratio of GFor capability (Volt-Ampere (VA)) over the total connected PE capability (VA). Such indicator is a drastic move from the traditionally accepted ratio of the PE production (Watt (W)) over Load consumption (W). Operation of 100% PE-based system forced us to redefine the need for inertia and short-circuit power. With no synchronous generation, the system still needs to sustain during the short surviving delay, before a fast and smart redispatch can balance the system. Accordingly, we can still define and require an electrical inertia, whose order of magnitude is lower than the present mechanical inertia in traditional system. The main reason behind is the faster action capability of PE-based resources to react to a load unbalance. To optimize the response of several sources in this context of higher dynamical system, new ancillary services have been designed, such has grid forming with limited energy. The short-circuit power was historically taken as an indicator of the grid-strength because the low transient reactance of synchronous gener-
ators had consequences on both the low sensibility of the voltage in small-signal sense, and on the large short-circuit current. In the case of GFor converters the two consequences are independent. The stability studies illustrate that the small-signal stiffness of the GFor inverters are of major importance to ensure the stability of the grid and should be the driver of converters sizing. Whereas the fault current can be limited with only consequences on protection scheme. With reference to WP4 of Migrate, we are confident that the protection scheme can adapt to this new behavior. To analyse a system of faster dynamics and with new stability indicators, simulation tools have been proposed, trying to bridge the gap between phasors models and EMT models.

The last part of the deliverable addresses the opportunities and the challenge of the transition from the present system to a 100 % PE system. The GFor converters increase the system dynamics, so that a new acceptable steady-state is reached faster. A faster dynamic might contribute positively to the stability of remaining synchronous generators of low-inertia systems. However, the new system dynamic will affect the stability all the already installed controls and create new adverse interactions.

The migration path still deserves extensive study to investigate the deployment plan of GFor sources, and the operating rules during the transition as the power system is likely to change from 100 % PE to low-inertia system with some synchronous generation, from a day to another. For further reading, [59] evaluates the economical impact of two deployment plans for GFor converters in high RES scenarios, compared to the commercially available solution based on synchronous condensers.
Acronyms

AC  Alternative Current. 38
DC  Direct Current. 38
FSM  Frequency Sensitive Mode. 10
GFol  Grid-Following. 7, 9, 13, 14, 24, 27, 31, 33, 34, 37
GFor  Grid-Forming. 5, 7, 14, 16, 22, 24, 31, 33, 34, 36, 38
LFDD  Low Frequency Demand Disconnection. 10
LFSM  Limited Frequency Sensitive Mode. 10
PE  Power Electronics. 2, 5, 7, 26, 29, 32, 34, 36, 38
PEIG  Power Electronics Interfaced Generation. 5
PSS  Power System Stabilizer. 13, 34
RoCoF  Rate of Change of Frequency. 10, 11, 33
SM  Synchronous Machine. 5, 7, 9, 13, 14, 16, 17, 19, 26, 29, 31, 33, 34, 37
VA  Volt-Ampere. 37
VSC  Voltage Source Converter. 7, 19, 21, 22, 24, 37
W  Watt. 37

References

[1] “Deliverable 3.2 local control and simulation tools for large transmission systems.”
https://www.h2020-migrate.eu/_Resources/Persistent/5c5beff0d5b7f8799253ae9b19f50a9cb6eb9f/D3.2%20-%20Local%20control%20and%20simulation%20tools%20for%20large%20transmission%20systems.pdf

[2] “Deliverable 3.3 new options for existing system services and needs for new system services.”
https://www.h2020-migrate.eu/_Resources/Persistent/0298d55a3f197e5b95e5476a88a7b840004cf/D3.3%20-%20New%20options%20for%20existing%20system%20services%20and%20needs%20for%20new%20system%20services.pdf


[5] “Deliverable 3.1 system needs and test cases.” [https://www.h2020-migrate.eu/_Resources/Persistent/85d17e132da9f44be3a67452723de5b585729cc5d/MIGRATE_D3-1_System%20Needs%20and%20Test%20Cases_v01.pdf](https://www.h2020-migrate.eu/_Resources/Persistent/85d17e132da9f44be3a67452723de5b585729cc5d/MIGRATE_D3-1_System%20Needs%20and%20Test%20Cases_v01.pdf).


“Igd for high penetration of power electronic interfaced power sources.”

“Vde-ar-n-4131 technical requirements for grid connection of hvdc system and direct-current connected ppm.”

“Deliverable 3.5 experimental results.”
tobeadded

G. Dominic and D. Florian, “Projected grid-forming control for current-limiting of power converters (i), 57th annual allerton conference on communication, control, and computing,” 2019.


P. Guhathakurta and X. Zhao, “Modelling approaches and stability assessment for 100% converter - based systems.”
https://share.epmlab.eu/index.php/s/Ak5tFLJTCuNNsDs?path=%2FPresentationspdfviewer

T. Qoria, F. Gruson, F. Colas, G. Denis, T. Prevost, and X. Guillaud, “Critical clearing time determination and enhancement of grid-forming converters embedding virtual impedance as current limitation algorithm,”


T. Qoria, T. Prevost, G. Denis, F. Gruson, F. Colas, and X. Guillaud, “Power converters classification and characterization in power transmission systems,”
[50] V. Akhmatov and C. F. Flytkær, “Call for adequate rms approach for grid stability assessment with a significant share of converter-interfaced units,”


[56] “D1.5 :power system risk analysis and mitigation measures.”


[59] C. Coujard, T. Prevost, G. Denis, B. Heimisson, and D. Wilson, “Impact analysis of the performed field and pilot tests.” Migrate Deliverable restricted access to Migrate Partners.